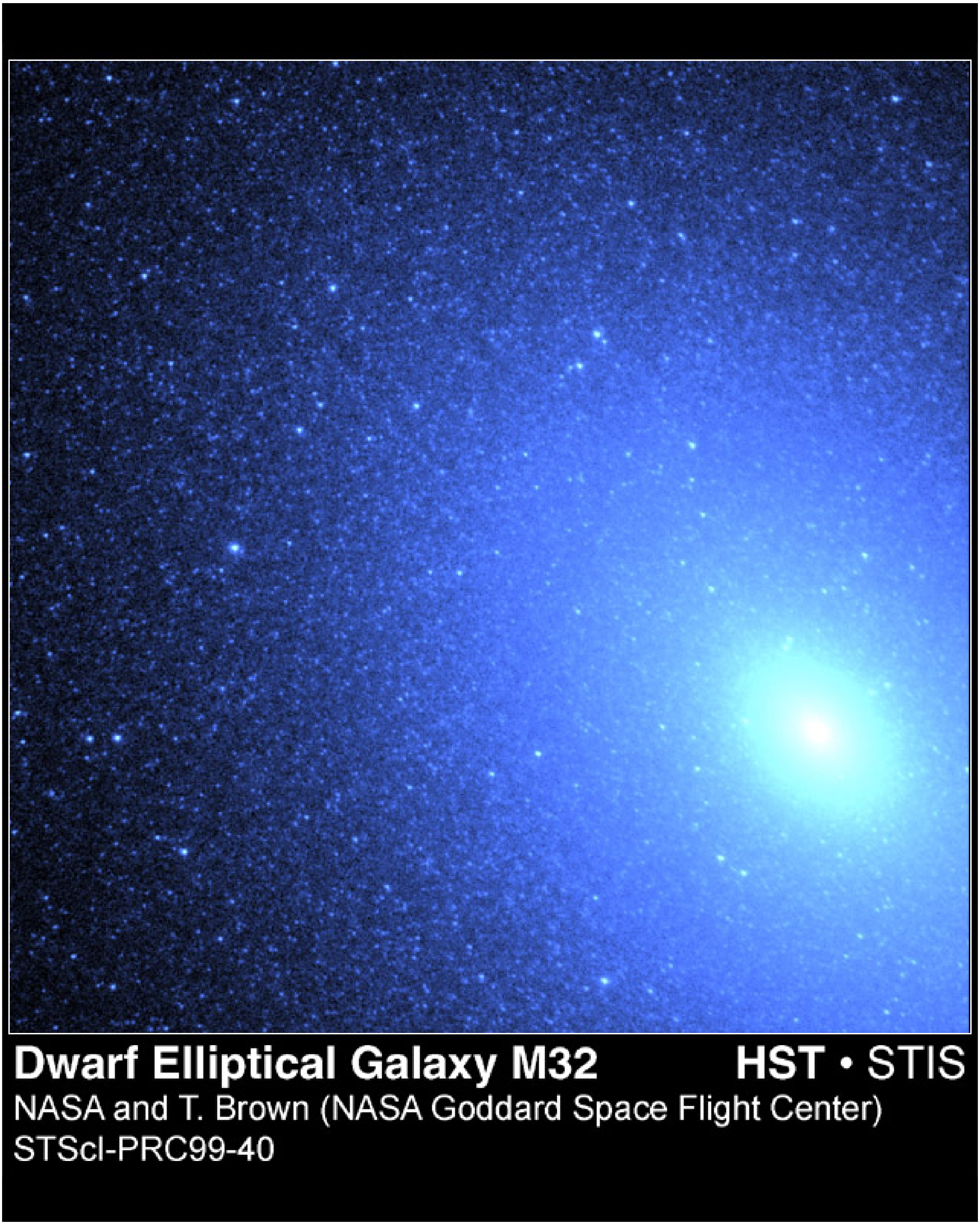
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Hubble Space Telescope's exquisite resolution has allowed astronomers to resolve, for the first time, hot blue stars deep inside an elliptical galaxy. The swarm of nearly 8,000 blue stars resembles a blizzard of snowflakes near the core (lower right) of the neighboring galaxy M32, located 2.5 million light-years away in the constellation Andromeda.

Hubble confirms that the ultraviolet light comes from a population of extremely hot helium-burning stars at a late stage in their lives. Unlike the Sun, which burns hydrogen into helium, these old stars exhausted their central hydrogen long ago, and now burn helium into heavier elements.

The observations, taken in October 1998, were made with the camera mode of the Space Telescope Imaging Spectrograph (STIS) in ultraviolet light. The STIS field of view is only a small portion of the entire galaxy, which is 20 times wider on the sky. For reference, the full moon is 70 times wider than the STIS field-of-view. The bright center of the galaxy was placed on the right side of the image, allowing fainter stars to be seen on the left side of the image.

Thirty years ago, the first ultraviolet observations of elliptical galaxies showed that they were surprisingly bright when viewed in ultraviolet light. Before those pioneering UV observations, old groups of stars were assumed to be relatively cool and thus extremely faint in the ultraviolet. Over the years since the initial discovery of this unexpected ultraviolet light, indirect evidence has accumulated that it originates in a population of old, but hot, helium-burning stars. Now Hubble provides the first direct visual evidence.

Nearby elliptical galaxies are thought to be relatively simple galaxies comprised of old stars. Because they are among the brightest objects in the Universe, this simplicity makes them useful for tracing the evolution of stars and galaxies.

Early Cosmology:

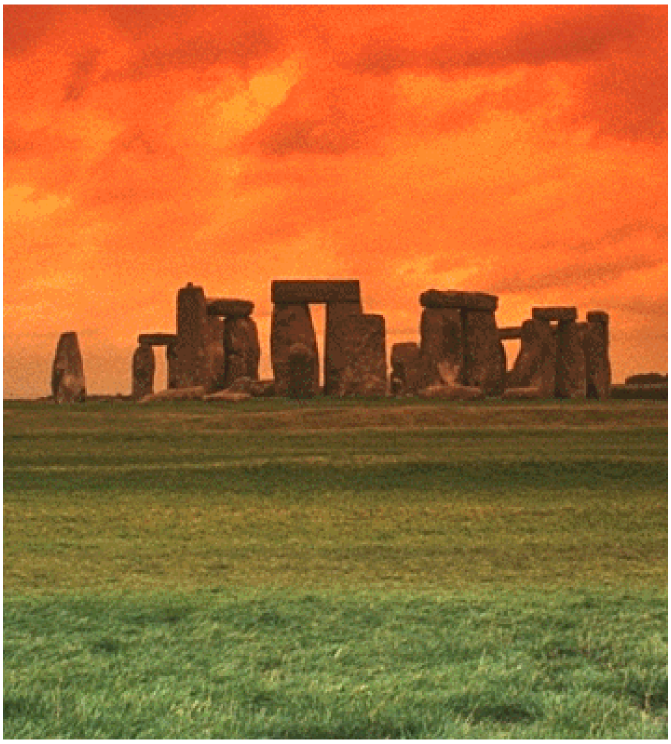
Cosmology is the study of the Universe and its components, how it formed, how its has evolved and what is its future. Modern cosmology grew from ideas before recorded history. Ancient man asked questions such as "What's going on around me?" which then developed into "How does the Universe work?", the key question that cosmology asks.

Many of the earliest recorded scientific observations were about cosmology, and pursue of understanding has continued for over 5000 years. Cosmology has exploded in the last 10 years with radically new information about the structure, origin and evolution of the Universe obtained through recent technological advances in telescopes and space observatories and bascially has become a search for the understanding of not only what makes up the Universe (the objects within it) but also its overall architecture.



Modern cosmology is on the borderland between science and philosophy, close to philosophy because it asks fundamental questions about the Universe, close to science since it looks for answers in the form of empirical understanding by observation and rational explanation. Thus, theories about cosmology operate with a tension between a philosophical urge for simplicity and a wish to include all the Universe's features versus the shire complexitied of it all.

Very early cosmology, from Neolithic times of 20,000 to 100,000 years ago, was extremely local. The Universe was what you immediately interacted with. Things outside your daily experience appeared supernatural, and so we call this time the Magic Cosmology.



Later in history, 5,000 to 20,000 years ago, humankind begins to organize themselves and develop what we now call culture. A greater sense of permanence in your daily existences leads to the development of myths, particularly creation myths to explain the origin of the Universe. We call this the Mythical Cosmology.




The third stage, what makes up the core of modern cosmology grew out of ancient Greek, later Christian, views. The underlying theme here is the use of observation and experimentation to search for simple, universal laws. We call this the Geometric Cosmology.

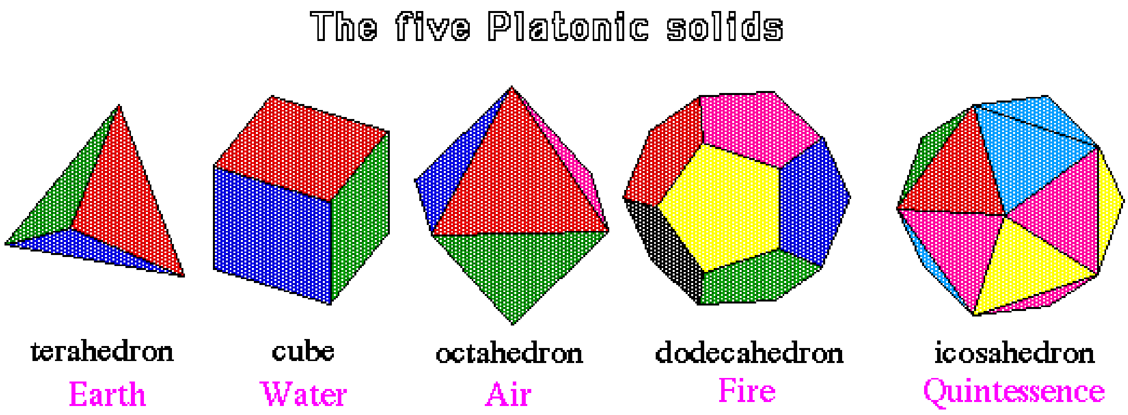


The earliest beginnings of science was to note that there exist patterns of cause and effect that are manifestations of the Universe's rational order. We mostly develop this idea as small children (touch hot stove = burn/pain). But the extrapolation of a rational order to cosmology requires a leap of faith in the beginning years of science, later supported by observation and experimentation.

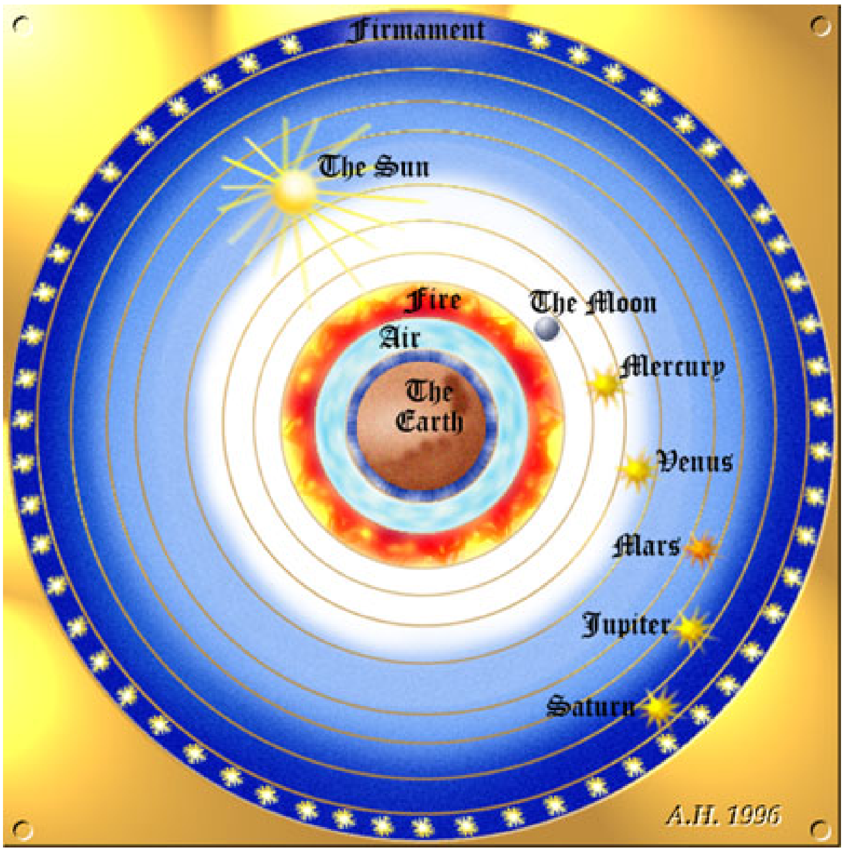
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## Greek Cosmology

The earliest cosmology was an extrapolation of the Greek system of four elements in the Universe (earth, water, fire, air) and that everything in the Universe is made up of some combination of these four primary elements. In a seemlingly unrelated discovery, Euclid, a Greek mathematician, proofed that there are only five solid shapes that can be made from simple polygons (the triangle, square and hexagon). Plato, strongly influenced by this pure mathematical discovery, revised the four element theory with the proposition that there were five elements to the Universe (earth, water, air, fire and quintessence) in correspondence with the five regular solids.




Each of these five elements occupied a unique place in the heavens (earth elements were heavy and, therefore, low; fire elements were light and located up high). Thus, Plato's system also became one of the first cosmological models and looked something like the following diagram:

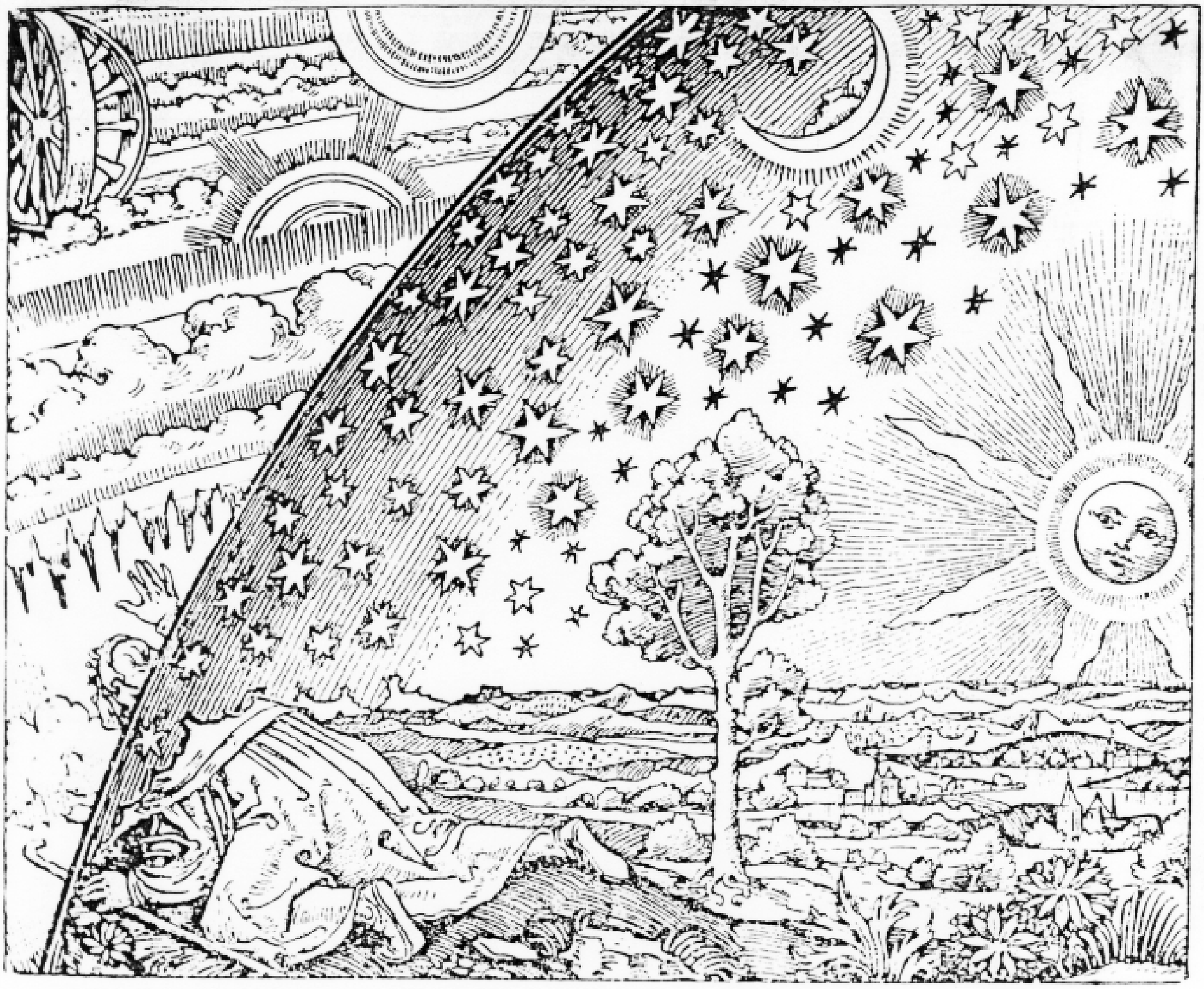



Like any good scientific model, this one offers explanations and various predictions. For example, hot air rises to reach the sphere of Fire, so heated balloons go up. Note that this model also predicts some incorrect things, such as all the planets revolve around the Earth, called the geocentric theory.

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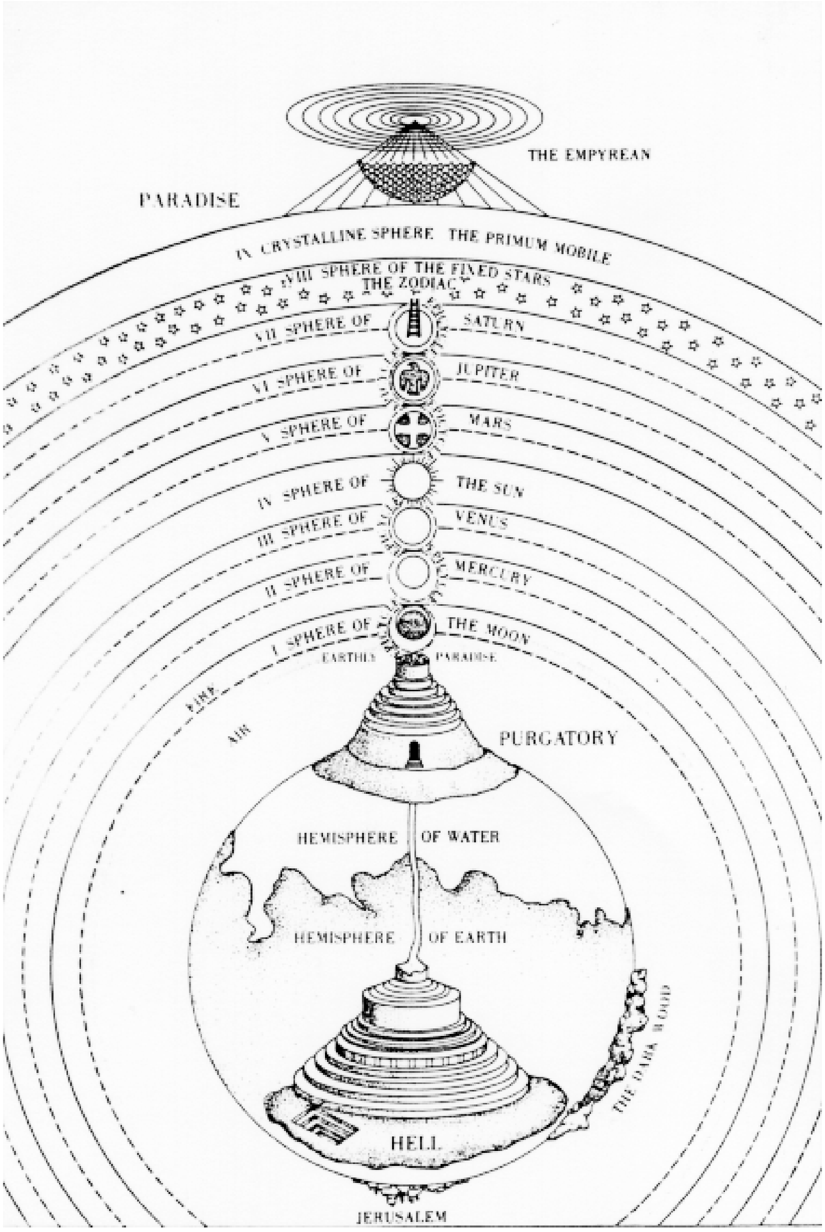
Middle Ages

The distinction between what mades up matter (the primary elements) and its form became a medieval Christian preoccupation, with the sinfulness of the material world opposed to the holiness of the heavenly realm. The medieval Christian cosmology placed the heavens in a realm of perfection, derived from Plato's Theory of Forms

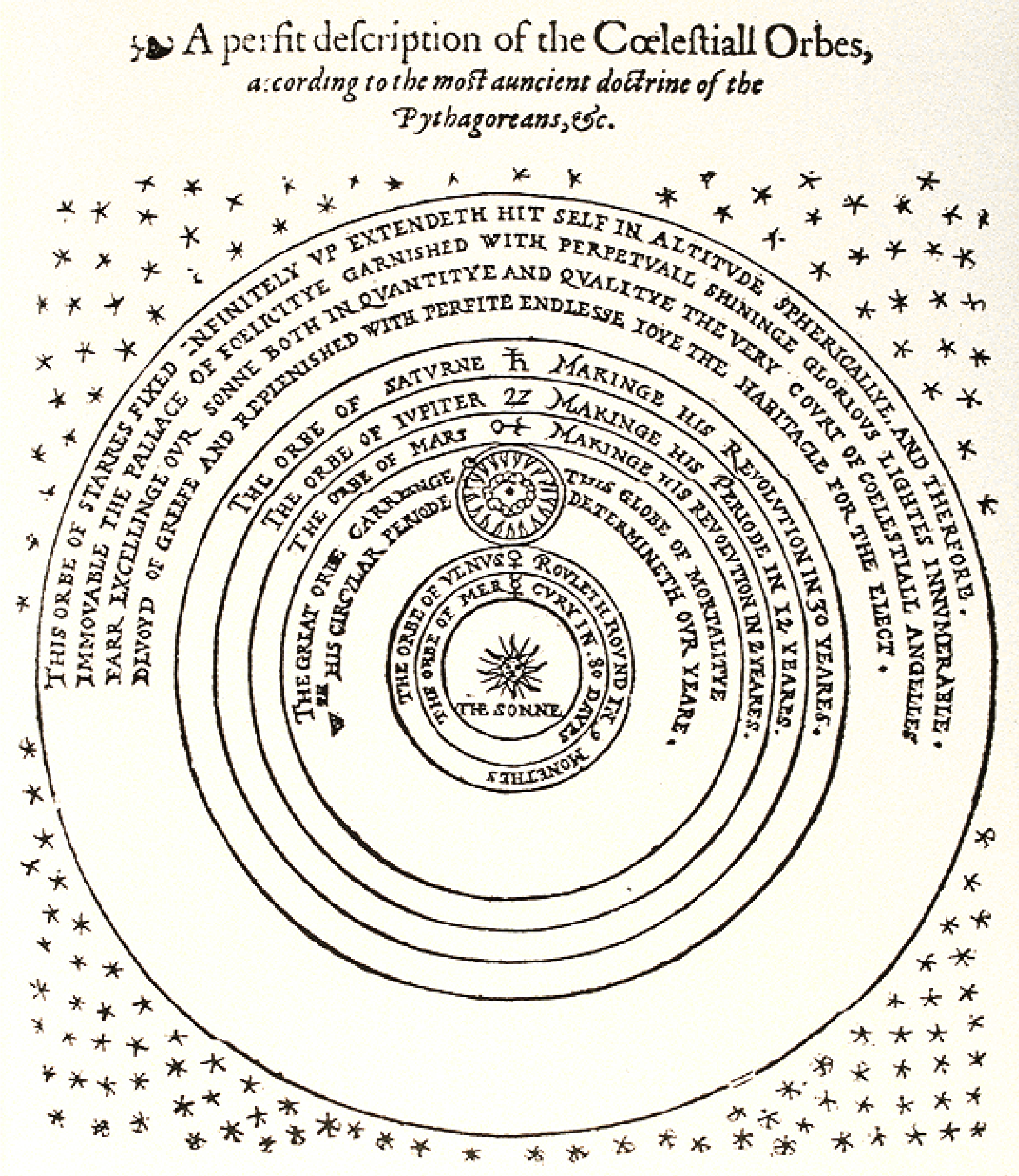


**SPACE WAS FINITE** and had a definite edge, according to the Aristotelian cosmology accepted during medieval times. Here a man is shown looking beyond the edge of space to the Empyrean abode of God beyond. The illustration is often said to be a 16th-century German woodcut; according to Owen Gingerich of Harvard University, it is more likely a piece of art nouveau that was apparently published for the first time in 1907 in *Weltall und Menschheit*, edited by Hans Kraemer. In either case the picture clearly demonstrates a dilemma posed by Immanuel Kant known as Kant's antinomy of space. Kant believed that the universe had to be finite in extent and homogeneous in composition, and that space had to obey the laws of Euclidean geometry. Actually, however, all those assumptions cannot be true at once. Newton, Leibniz and Einstein had different ways of resolving the dilemma, shown in illustrations on next two pages.

Before the scientific method was fully developed, many cosmological models were drawn from religious or inspirational sources. One such was the following scheme taken from Dante's `The Divine Comedy'.




The political and intellectual authority of the medieval church declined with time, leading to the creative anarchy of the Renaissance. This produced a scientific and philosophical revolution including the birth of modern physics. Foremost to this new style of thinking was a strong connection between ideas and facts (the scientific method).

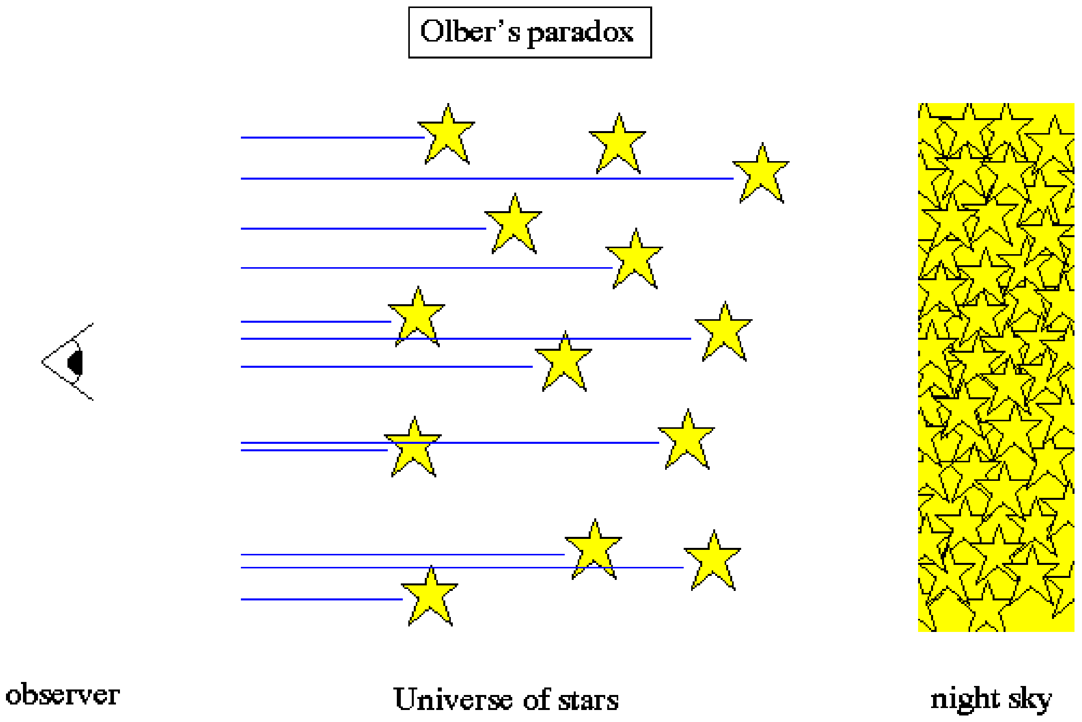



Since cosmology involves observations of objects very far away (therefore, very faint) advancement in our understanding of the cosmos has been very slow due to limits in our technology. This has changed dramatically in the last few years with the construction of large telescopes and the launch of space-based observatories.

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<u>Olber's Paradox</u>:

The oldest cosmological paradox concerns the fact that the night sky should appear as bright as the surface of the Sun in a very large (or infinite), ageless Universe.



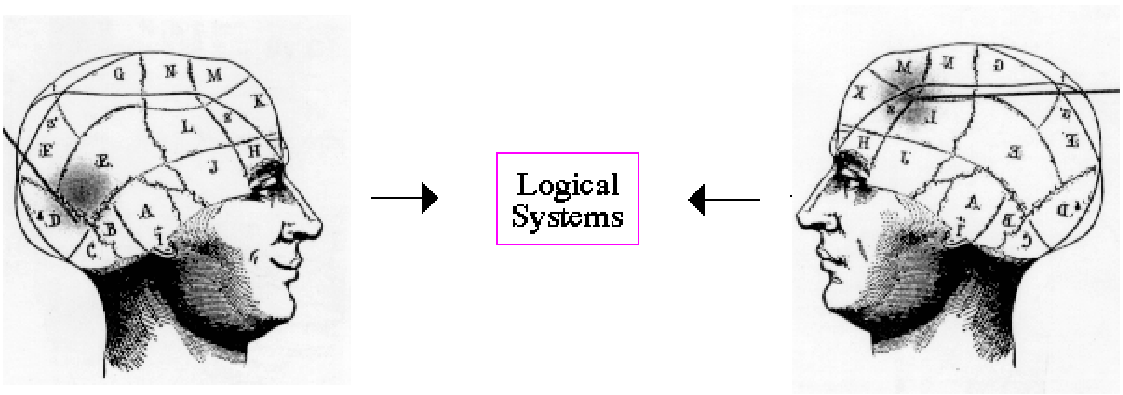

Note that the paradox cannot be resolved by assuming that parts of the Universe are filled with absorbing dust or dark matter, because eventually that material would heat up and emit its own light.

The resolution of Olber's paradox is found in the combined observation that 1) the speed of light is finite (although a very high velocity) and 2) the Universe has a finite age, i.e. we only see the light from parts of the Universe less than 15 billion light years away.

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Rationalism:

The main purpose of science is to trace, within the chaos and flux of phenomena, a consistent structure with order and meaning. This is called the philosophy of rationalism. The purpose of scientific understanding is to coordinate our experiences and bring them into a logical system.

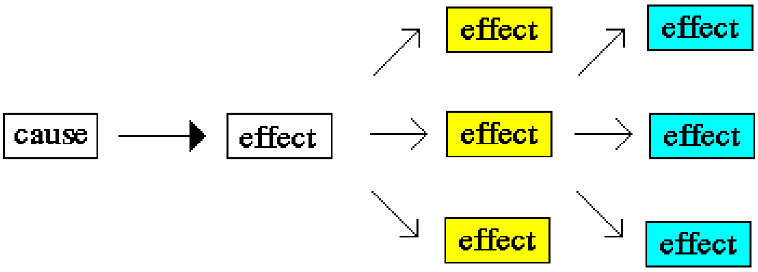



Thoughout history, intellectual efforts are directed towards the discovery of pattern, system and structure, with a special emphasis on order. Why? control of the unpredictable, fear of the unknown, and a person who seeks to understand and discover is called a scientist.

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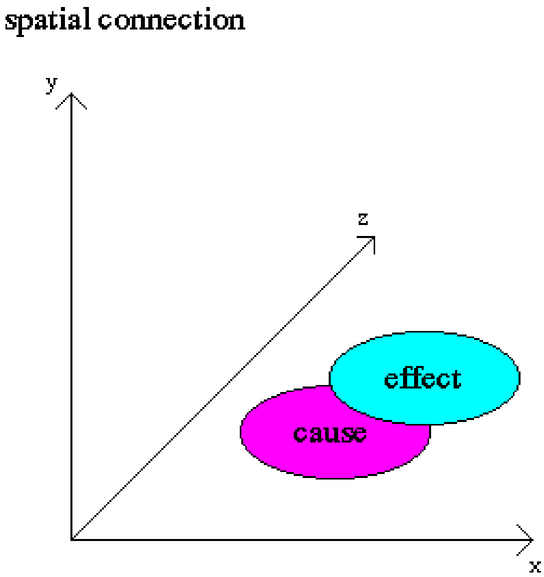
Cause+Effect:

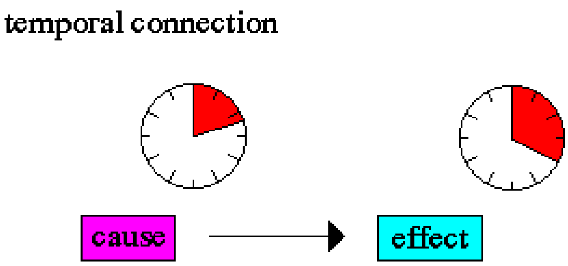
The foundation for rationalism rests squarely on the principle of locality, the idea that correlated events are related by a chain of causation.



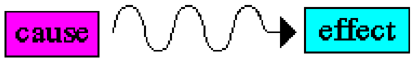

There are three components to cause and effect:

- contiguity in space
- temporal priority of the cause (i.e. its first)
- necessary connection



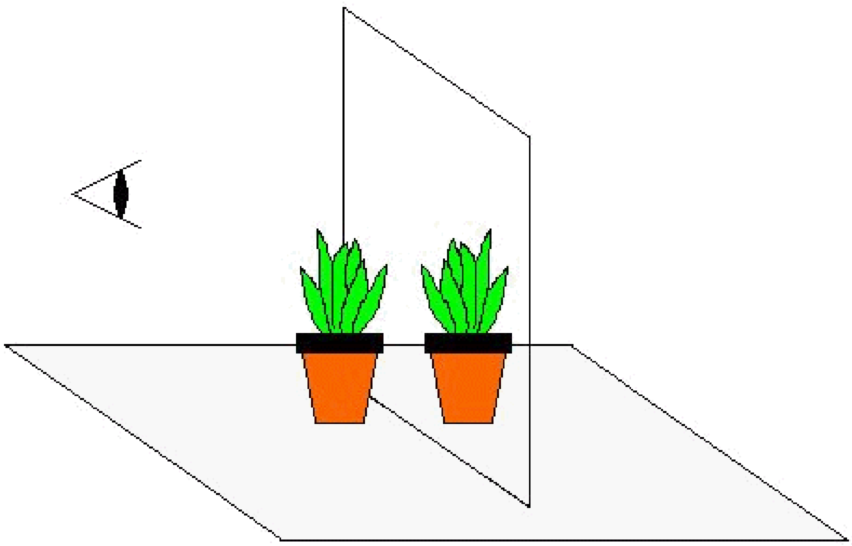






The necessary connection in cause and effect events is the exchange of energy, which is the foundation of information theory => knowledge is power (energy).

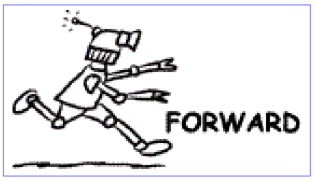
Also key to cause and effect is the concept that an object's existence and properties are independent of the observation or experiment and rooted in reality.



objects in a mirror are `unreal' in the sense of not having existence in the material world

Causal links build an existence of patterns that are a manifestation of the Universe's rational order. Does the chain of cause and effect ever end? Is there an `Initial Cause'?

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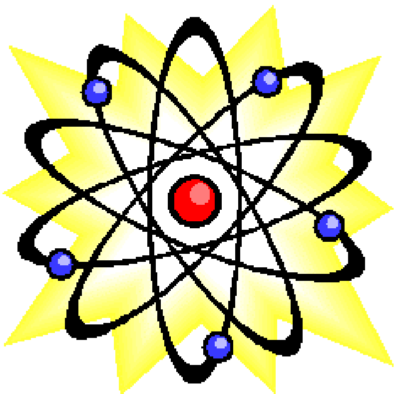


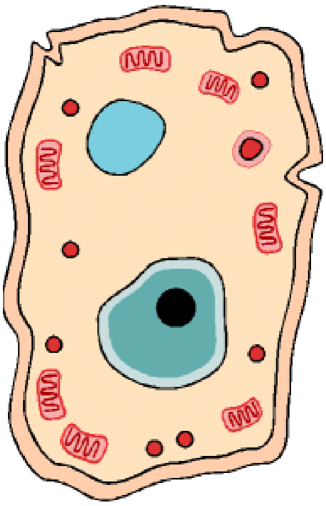

Science:

The tool of the philosophy of rationalism is called science. Science is any system of knowledge that is concerned with the physical world and its phenomena and entails unbiased observations and/or systematic experimentation. In general, a science involves a pursuit of knowledge covering general truths or the operations of fundamental laws of nature.



Science is far from a perfect instrument of knowledge, but it provides something that other philosophies often fail to provide, concrete results. Science is a ``candle in the dark'' to illuminate irrational beliefs or superstitions.

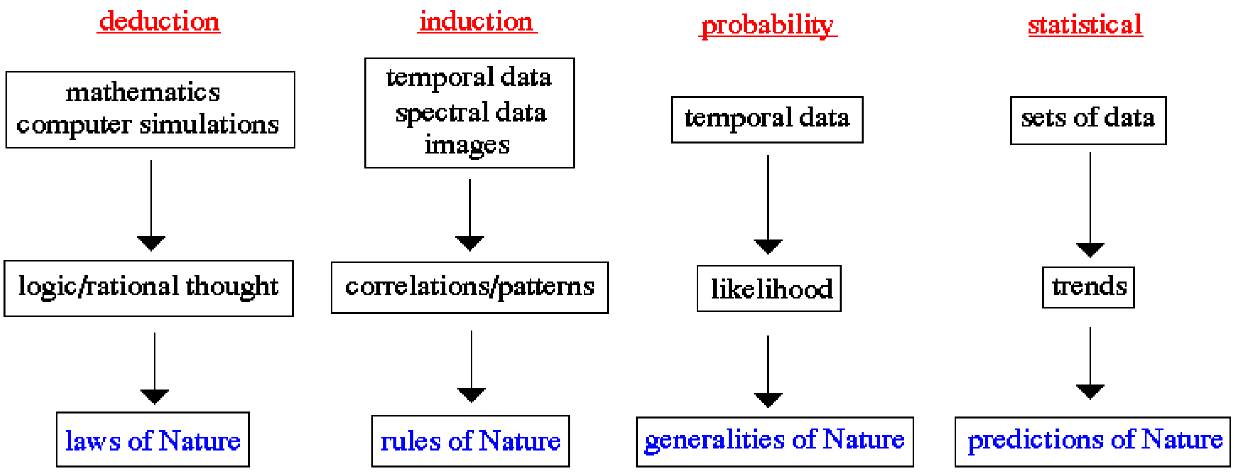




Science does not, by itself, advocate courses of human action, but it can certainly illuminate the possible consequences of alternative courses. In this regard, science is both imaginative and disciplined, which is central to its power of prediction.

The keystone to science is proof or evidence/data, which is not to be confused with certainty. Except in pure mathematics, nothing is known for certain (although much is certainly false). Central to the scientific method is a system of logic.

Scientific arguments of logic basically take on four possible forms; 1) the pure method of deduction, where some conclusion is drawn from a set of propositions (i.e. pure logic), 2) the method of induction, where one draws general conclusions from particular facts that appear to serve as evidence, 3) by probability, which passes from frequencies within a known domain to conclusions of stated likelihood, and 4) by statistical reasoning, which concludes that, on the average, a certain percentage of a set of entities will satisfy the stated conditions. To support these methods, a scientist also uses a large amount of skepticism to search for any fallacies in arguments.




The fact that scientific reasoning is so often successful is a remarkable property of the Universe, the dependability of Nature.

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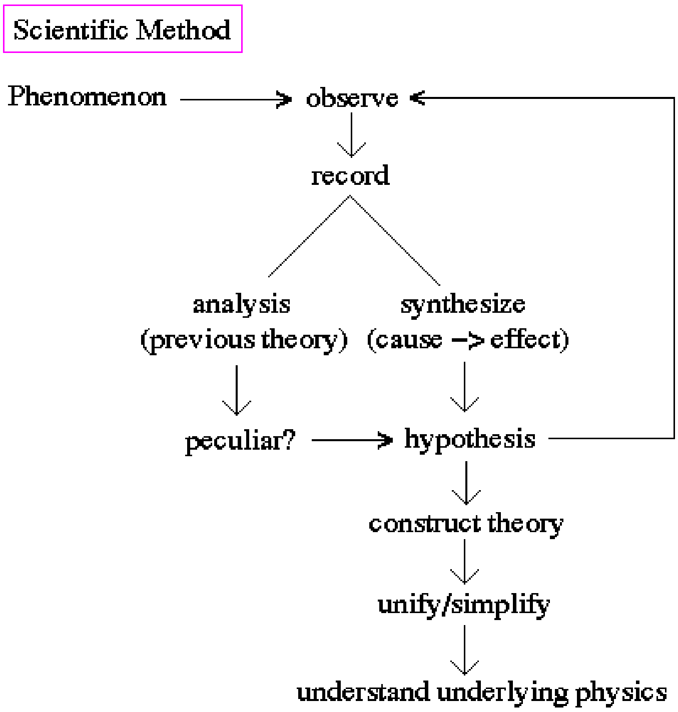
Scientific Method:

Of course, the main occupation of a scientist is problem solving with the goal of understanding the Universe. To achieve this goal, a scientist applies the scientific method. The scientific method is the rigorous standard of procedure and discussion that sets reason over irrational belief. The process has four steps:

- observation/experimentation
- deduction
- hypothesis
- falsification

Note the special emphasis on falsification, not verification. A powerful hypothesis is one that is actually highly vulnerable to falsification and that can be tested in many ways.

The underlying purpose of the scientific method is the construction of simplifying ideas, models and theories, all with the final goal of understanding.



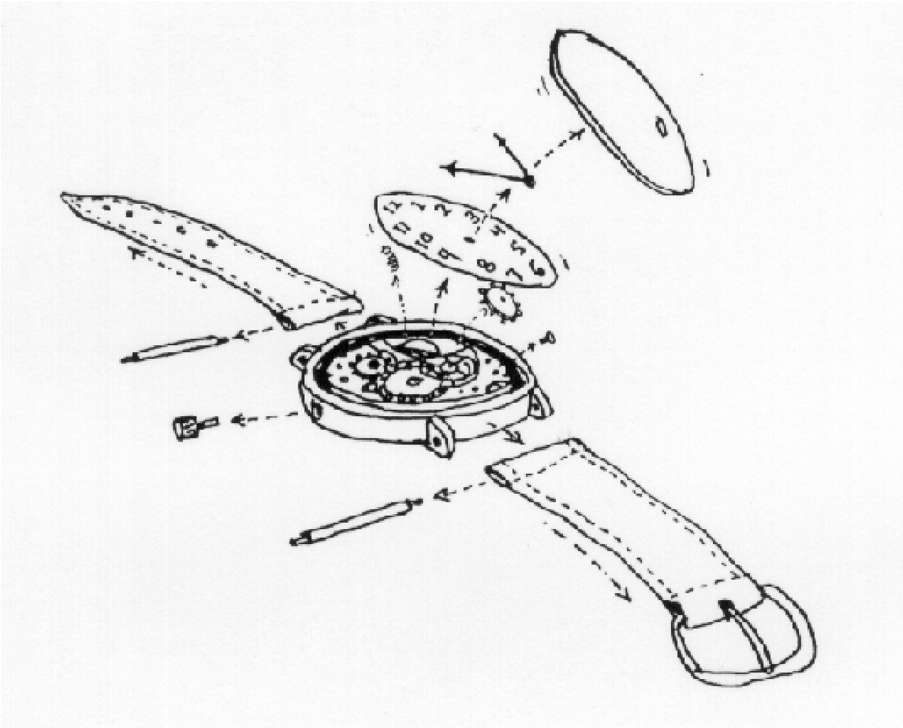
The only justification for our concepts of `electron', `mass', `energy', or `time' is that they serve to represent the complexity of our experiences. It is an ancient debate on whether humankind invents or discovers physical laws. Whether natural laws exist independent of our culture or whether we impose these laws on Nature as crude approximations.

Science can be separated from pseudo-science by the principle of falsifiability, the concept that ideas must be capable of being proven false in order to be scientifically valid.

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Reductionism:

Reductionism is the belief that any complex set of phenomena can be defined or explained in terms of a relatively few simple or primitive ones.



For example, atomism is a form of reductionism in that it holds that everything in the Universe can be broken down into a few simple entities (elementary particles) and laws to describe the interactions between them. This idea became modern chemistry which reduces all chemical properties to ninety or so basic elements (kinds of atoms) and their rules of combination.

Reductionism is very similar to, and has its roots from, Occam's Razor, which states that between competing ideas, the simplest theory that fits the facts of a problem is the one that should be selected.

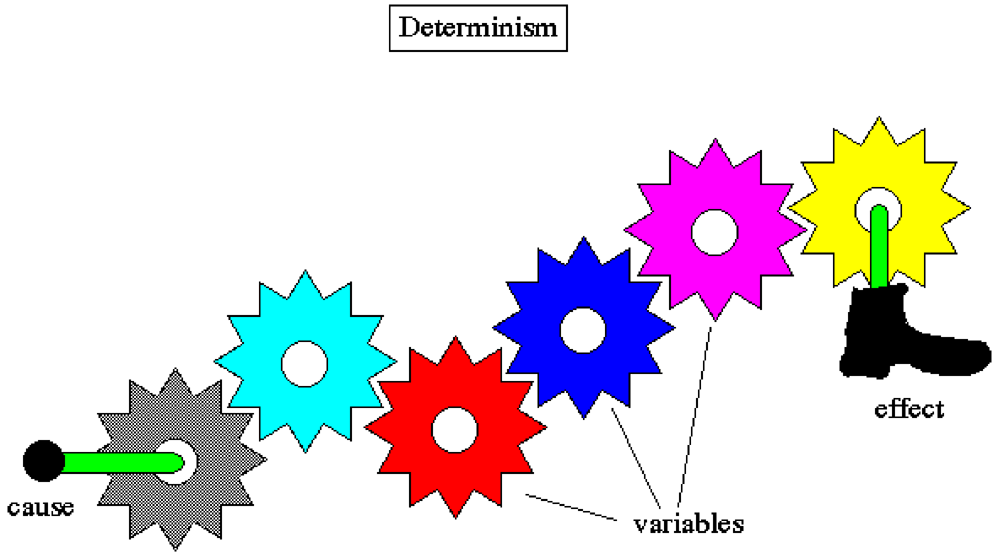
Reductionism was widely accepted due to its power in prediction and formulation. It is, at least, a good approximation of the macroscopic world (although it is completely wrong for the microscope world, see quantum physics).

Too much success is a dangerous thing since the reductionist philosophy led to a wider paradigm, the methodology of scientism, the view that everything can and should be reduced to the properties of matter (materialism) such that emotion, aesthetics and religious experience can be reduced to biological instinct, chemical imbalances in the brain, etc. The 20th century reaction against reductionism is relativism. Modern science is somewhere in between.

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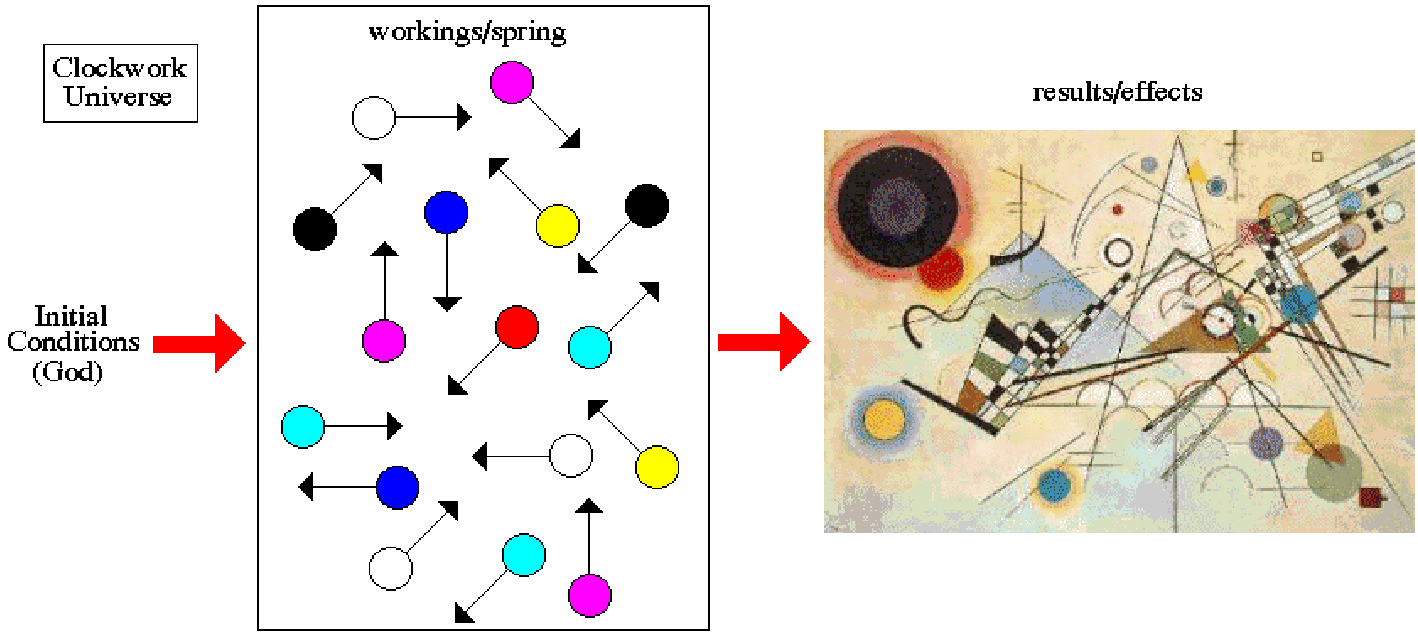
Determinism:

Closely associated with reductionism is determinism, the philosophy that everything has a cause, and that a particular cause leads to a unique effect. Another way of stating this is that for everything that happens there are conditions such that, given them, nothing else could happen, the outcome is determined.




Determinism implies that everything is predictable given enough information.

Newtonian or classical physics is rigidly determinist, both in the predictions of its equations and its foundations, there is no room for chance, surprise or creativity. Everything is as it has to be, which gave rise to the concept of a clockwork Universe.

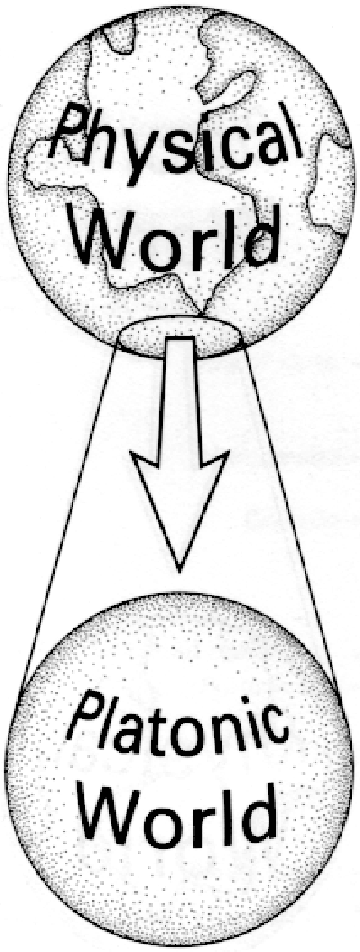



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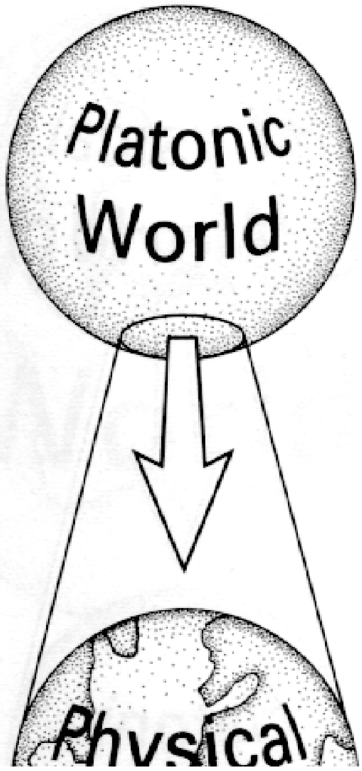
Mathematics and Science:

The belief that the underlying order of the Universe can be expressed in mathematical form lies at the heart of science and is rarely questioned. But whether mathematics a human invention or if it has an independent existence is a question for metaphysics.

There exists two schools of thought. One that mathematical concepts are mere idealizations of our physical world. The world of absolutes, what is called the Platonic world, has existence only through the physical world. In this case, the mathematical world would be though of as emerging from the world of physical objects.




The other school is attributed to Plato, and finds that Nature is a structure that is precisely governed by timeless mathematical laws. According to Platonists we do not invent mathematical truths, we discover them. The Platonic world exists and physical world is a shadow of the truths in the Platonic world. This reasoning comes about when we realize (through thought and experimentation) how the behavior of Nature follows mathematics to an extremely high degree of accuracy. The deeper we probe the laws of Nature, the more the physical world disappears and becomes a world of pure math.



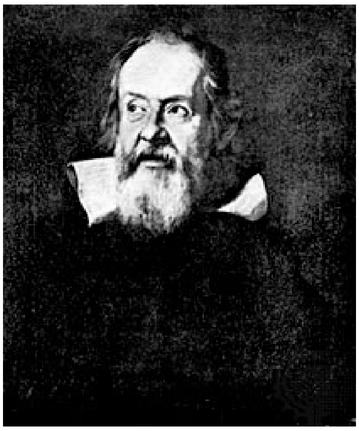



Mathematics transcends the physical reality that confronts our senses. The fact that mathematical theorems are discovered by several investigators indicates some objective element to mathematical systems. Since our brains have evolved to reflect the properties of the physical world, it is of no surprise that we discover mathematical relationships in Nature.

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Galileo's Laws of Motion:

Galileo Galilei stressed the importance of obtaining knowledge through precise and quanitiative experiment and observation. Man and Nature are considered distinct and experiment was seen as a sort of dialogue with Nature. Nature's rational order, which itself is derived from God, was manifested in definite laws.



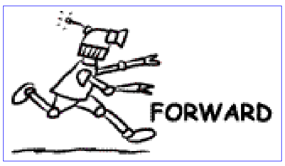
Aside from his numerous inventions, Galileo also laid down the first accurate laws of motion for masses. Galileo realized that all bodies accelerate at the same rate regardless of their size or mass. Everyday experience tells you differently because a feather falls slower than a cannonball. Galileo's genius lay in spotting that the differences that occur in the everyday world are in incidental complication (in this case, air friction) and are irrelevant to the real underlying properties (that is, gravity) which is pure mathematical in its form. He was able to abstract from the complexity of real-life situations the simplicity of an idealized law of gravity.

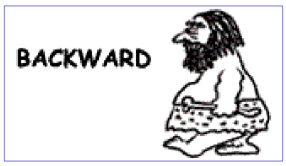
Key among his investigations are:

- developed the concept of motion in terms of velocity (speed and direction) through the use of inclined planes.
- developed the idea of force, as a cause for motion.
- determined that the natural state of an object is rest or uniform motion, i.e. objects always have a velocity, sometimes that velocity has a magnitude of zero = rest.
- objects resist change in motion, which is called inertia.

Galileo also showed that objects fall with the same speed regardless of their mass. The fact that a feather falls slowly than a steel ball is due to amount of air resistance that a feather experiences (alot) versus the steel ball (very little).

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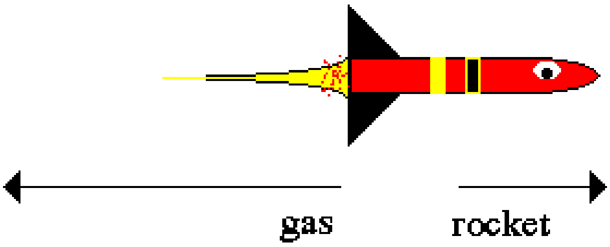



## Newtonian Physics:

Newtonian or classical physics is reductionist, holding that all physical reality can be reduced to a few particles and the laws and forces acting among them. Newtonian physics is free of spiritual or psychological forces = emphasis on objectivity.

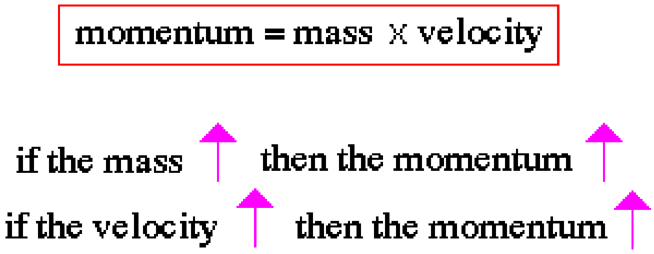
Newton expanded on the work of Galileo to better define the relationship between energy and motion. In particular, he developed the following concepts:

- the change in velocity of an object is called acceleration, and is caused by a force

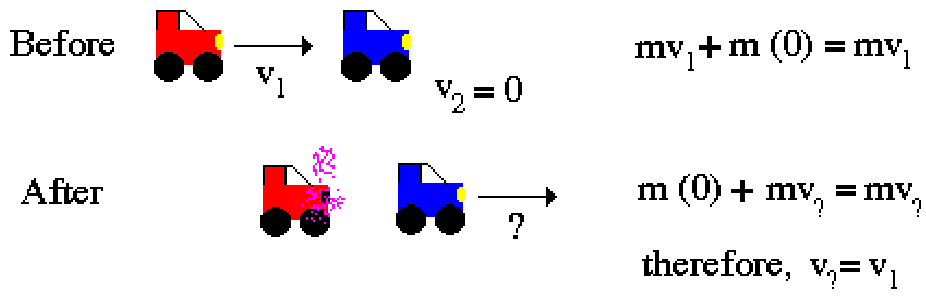


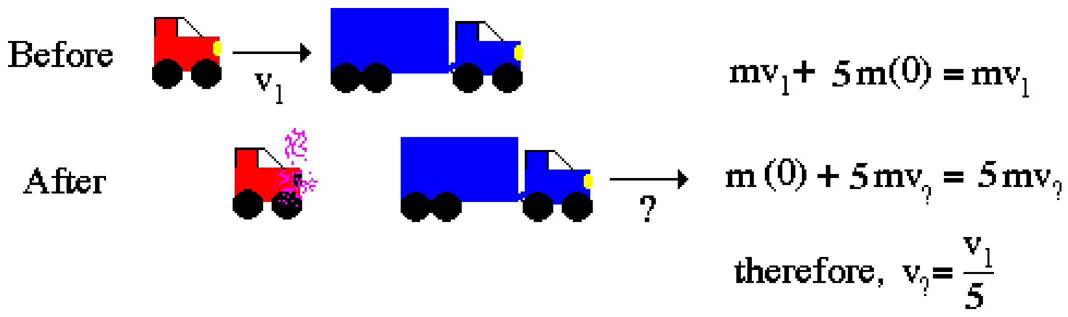

- The resistance an object has to changes in velocity is called inertia and is proportional to its mass

- Momentum is a quantity of motion (kinetic) energy and is equal to mass times velocity




Key to the clockwork universe concept are the conservation laws in Newtonian physics. Specifically, the idea that the total momentum of an interaction is conserved (i.e. it is the same before and after).



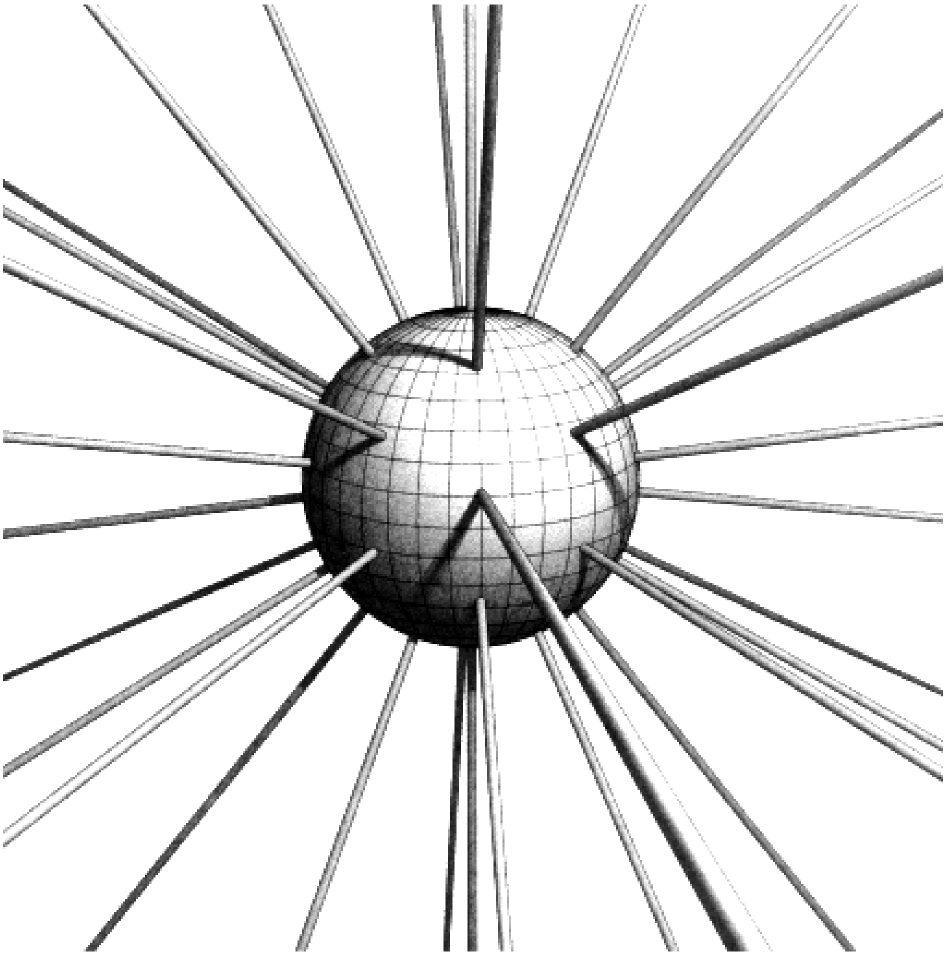




Conservation laws allow detailed predictions from initial conditions, a highly deterministic science.

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Newton's Law of Universal Gravitation:

Galileo was the first to notice that objects are ``pulled'' towards the center of the Earth, but Newton showed that this same force (gravity) was responsible for the orbits of the planets in the Solar System.



Objects in the Universe attract each other with a force that varies directly as the product of their masses and inversely as the square of their distances

**Newton's Law of Universal Gravitation**

The force of gravity, $F_g$, is given by

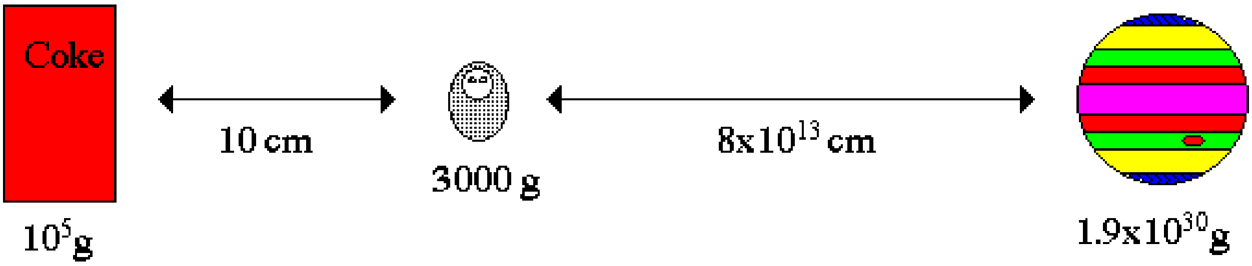
$$F_g = \frac{G\, m_1 m_2}{R^2}$$

where,

$G$ = gravitational constant = $6.668 \times 10^{-8}$ dynes cm$^3$ g$^{-2}$
$m_1$ = mass of object #1
$m_2$ = mass of object #2
$R$ = distance between the objects

All masses, regardless of size, attract other masses with gravity. You don't notice the force from nearby objects because their mass is so small compared to the mass of the Earth. Consider the following example:

Example: what is the force of gravity from Jupiter on you at birth compared to the force of gravity from a nearby Coke machine?

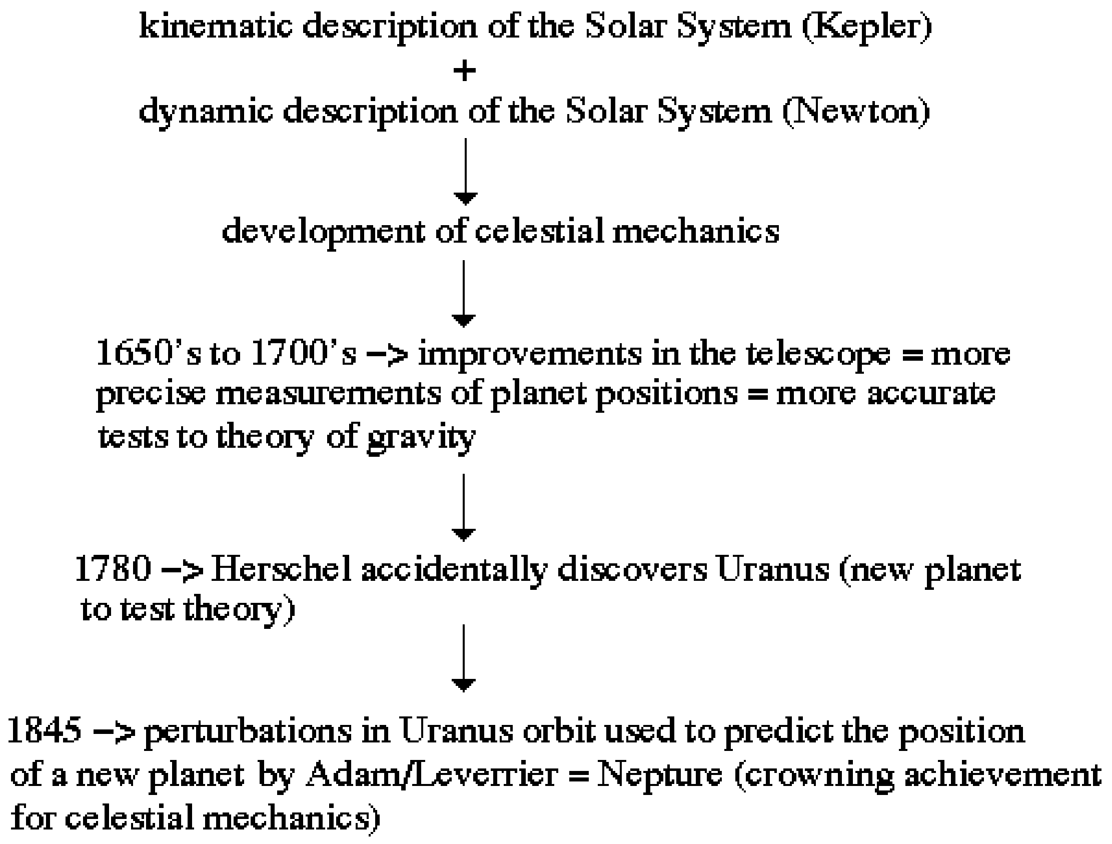



$$F_{Coke} = \frac{G(10^5 g)(3000g)}{(10\ cm)^2} = 2x10^{-1}\ dynes$$

$$F_{Jupiter} = \frac{G(1.9x10^{30} g)(3000g)}{(8x10^{13}\ cm)^2} = 5.9x10^{-2}\ dynes$$

therefore, the force of gravity from the Coke machine is about 3 times more than the force of gravity from Jupiter.

Newton's development of the underlying cause of planetary motion, gravity, completed the solar system model begun by the Babylonians and early Greeks. The mathematical formulation of Newton's dynamic model of the solar system became the science of celestial mechanics, the greatest of the deterministic sciences.

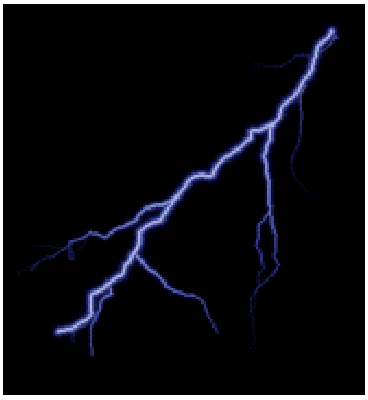



Although Newtonian mechanics was the grand achievement of the 1700's, it was by no means the final answer. For example, the equations of orbits could be solved for two bodies, but could *not* be solved for three or more bodies. The three body problem puzzled astronomers for years until it was learned that some mathematical problems suffer from deterministic chaos, where dynamical systems have apparently random or unpredictable behavior.

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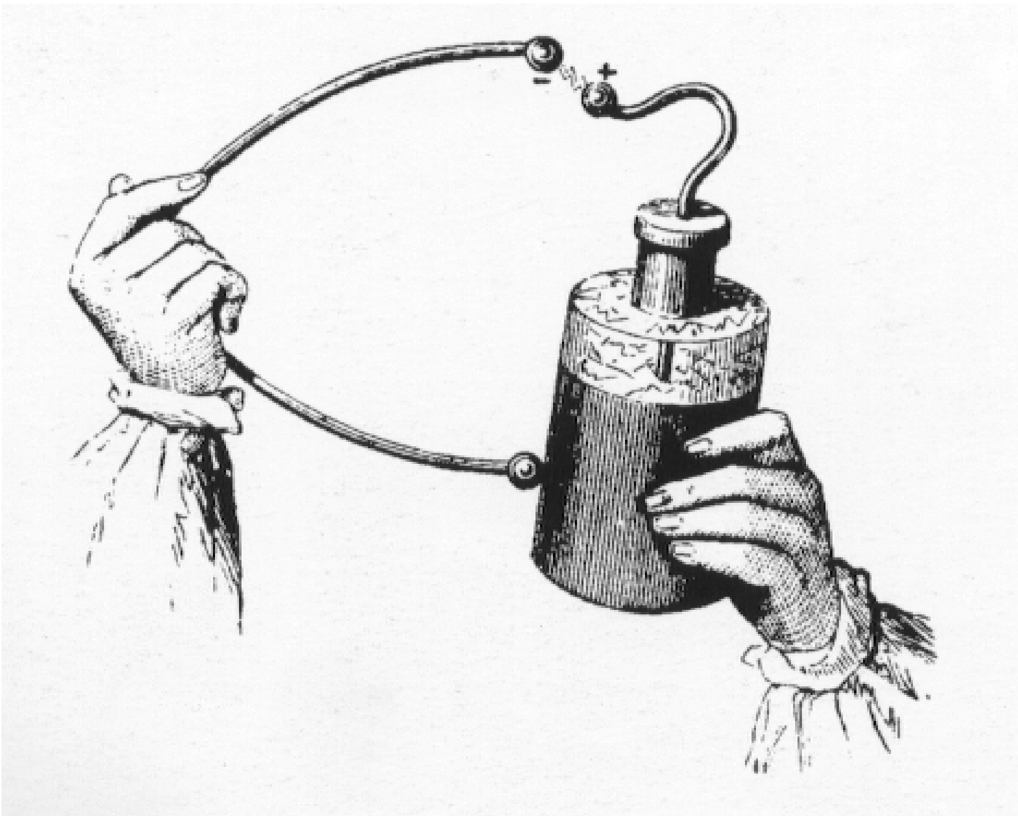
Electricity:

The existence of electricity, the phenomenon associated with stationary or moving electric charges, has been known since the Greeks discovered that amber, rubbed with fur, attracted light objects such as feathers. Ben Franklin proved the electrical nature of lightning (the famous key experiment) and also established the conventional use of negative and positive types of charges.



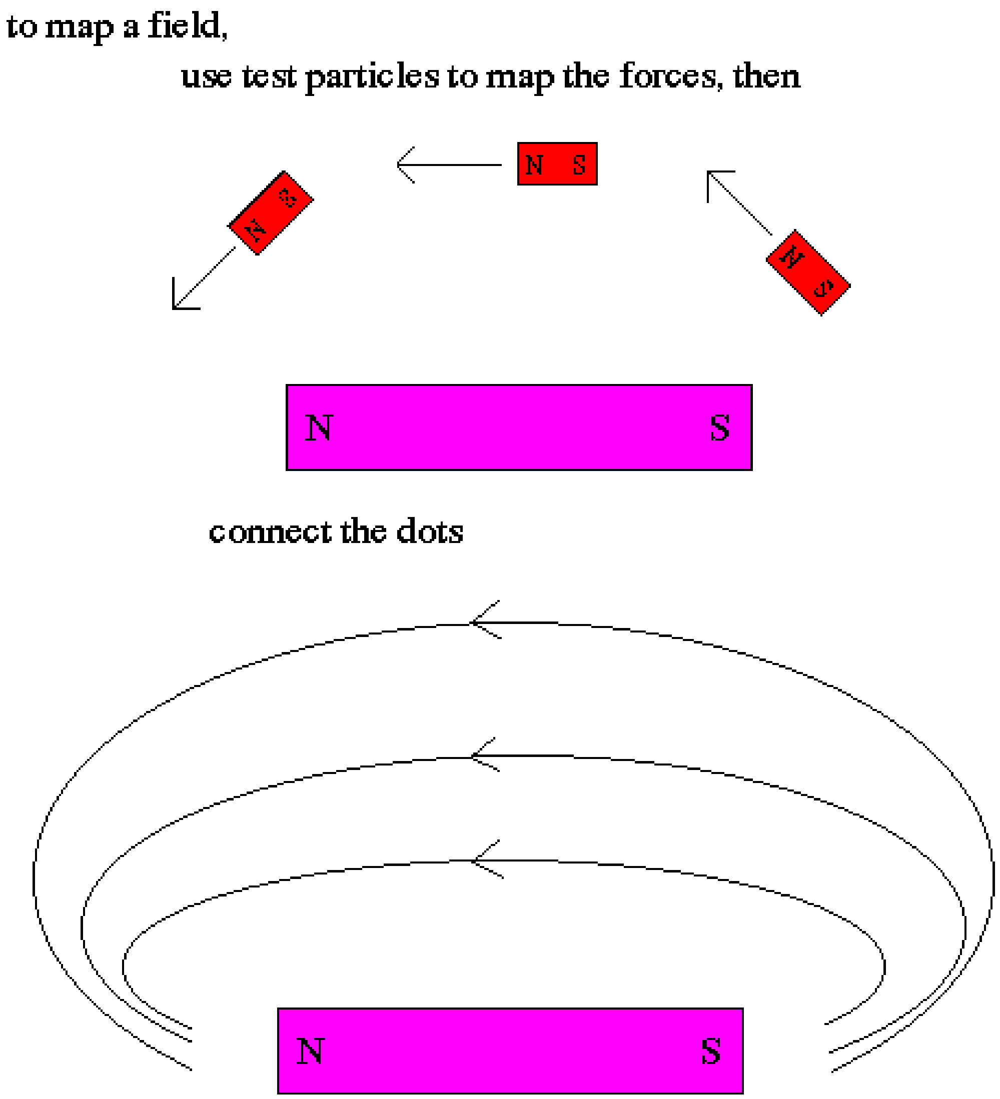
By the 18th century, physicist Charles Coulomb defined the quantity of electricity (electric charge) later known as a coulomb, and determined the force law between electric charges, known as Coulomb's law. Coulomb's law is similar to the law of gravity in that the electrical force is inversely proportional to the distance of the charges squared, and proportional to the product of the charges.

By the end of the 18th century, we had determined that electric charge could be stored in a conducting body if it is insulated from its surroundings. The first of these devices was the Leyden jar. consisted of a glass vial, partly filled with sheets of metal foil, the top of which was closed by a cork pierced with a wire or nail. To charge the jar, the exposed end of the wire is brought in contact with a friction device.



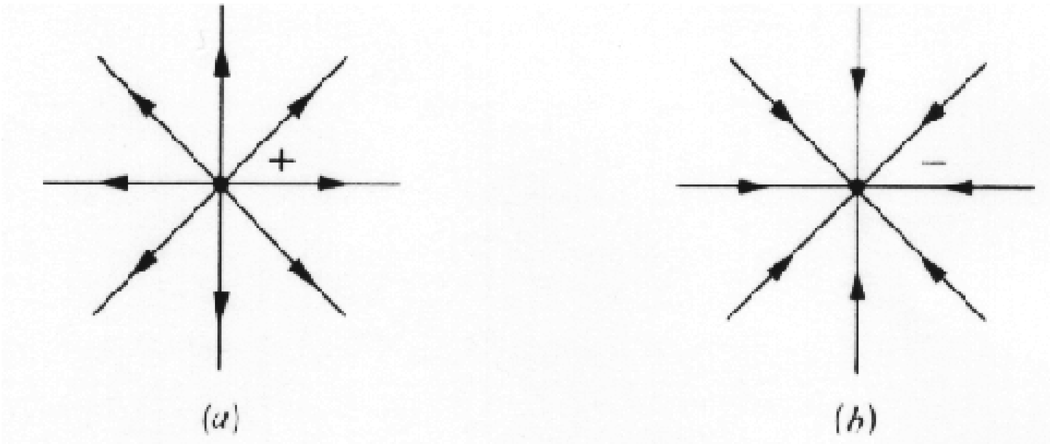
Modern atomic theory explains this as the ability of atoms to either lose or gain an outer electron and thus exhibit a net positive charge or gain a net negative charge (since the electron is negative). Today we know that the basic quantity of electric charge is the electron, and one coulomb is about $6.24 \times 10^{18}$ electrons.

The battery was invented in the 19th century, and electric current and static electricity were shown to be manifestations of the same phenomenon, i.e. current is the motion of electric charge. Once a laboratory curiosity, electricity becomes the focus of industrial concerns when it is shown that electrical power can be transmitted efficiently from place to place and with the invention of the incandescent lamp.

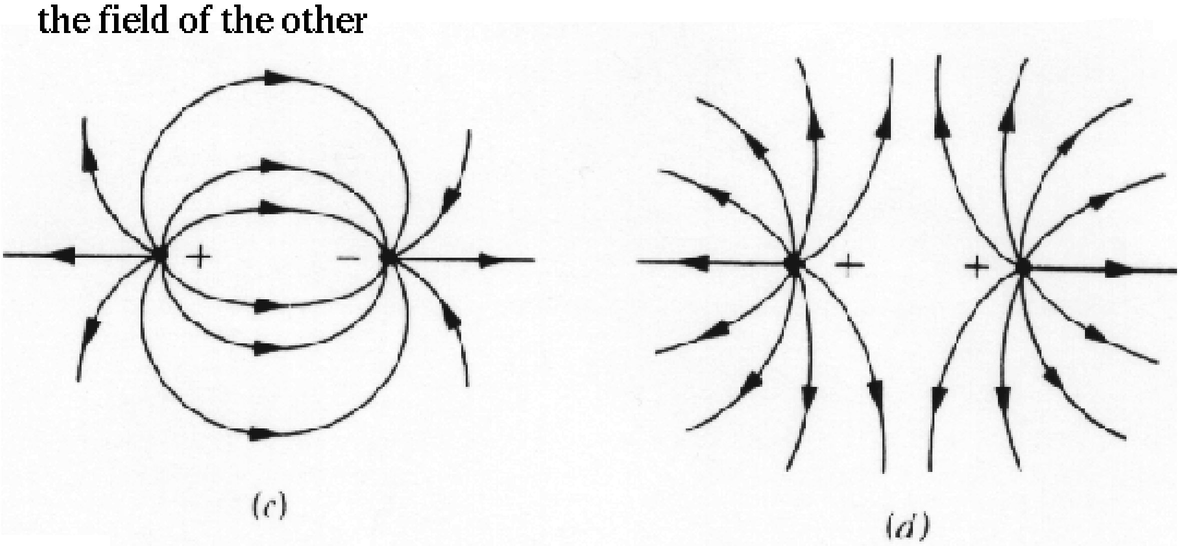



The discovery of Coulomb's law, and the behavior or motion of charged particles near other charged particles led to the development of the electric field concept. A field can be considered a type of energy in space, or energy with position. A field is usually visualized as a set of lines surrounding the body, however these lines do not exist, they are strictly a mathematical construct to describe motion. Fields are used in electricity, magnetism, gravity and almost all aspects of modern physics.

A single, isolated charge acts as a source of an electric field (a) or a sink (b)




The field of two charges has a complicated shape, each charge disturbs the field of the other




Opposite charges attract reflected by the field lines which link them together (c). Like charges repel, no field lines connect them (d).

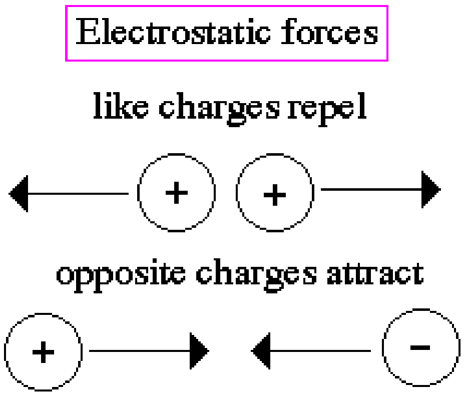
An electric field is the region around an electric charge in which an electric force is exerted on another charge. Instead of considering the electric force as a direct interaction of two electric charges at a distance from each other, one charge is considered the source of an electric field that extends outward into the surrounding space, and the force exerted on a second charge in this space is considered as a direct interaction between the electric field and the second charge.

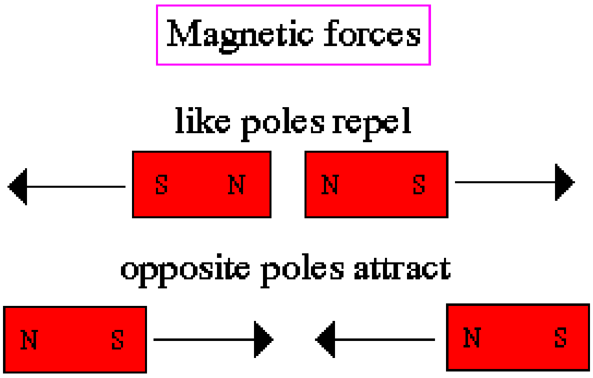
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<u>Magnetism</u>:

Magnetism is the phenomenon associated with the motion of electric charges,

although the study of magnets was very confused before the 19th century because of the existence of ferromagnets, substances such as iron bar magnets which maintain a magnetic field where no obvious electric current is present (see below). Basic magnetism is the existence of magnetic fields which deflect moving charges or other magnets. Similar to electric force in strength and direction, magnetic objects are said to have `poles' (north and south, instead of positive and negative charge). However, magnetic objects are always found in pairs, there do not exist isolated poles in Nature.




The most common source of a magnetic field is an electric current loop. The motion of electric charges in a pattern produces a magnetic field and its associated magnetic force. Similarly, spinning objects, like the Earth, produce magnetic fields, sufficient to deflect compass needles.

Today we know that permanent magnets are due to dipole charges inside the magnet at the atomic level. A dipole charge occurs from the spin of the electron around the nucleus of the atom. Materials (such as metals) which have incomplete electron shells will have a net magnetic moment. If the material has a highly ordered crystalline pattern (such as iron or nickel), then the local magnetic fields of the atoms become coupled and the material displays a large scale bar magnet behavior.

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Electromagnetism:

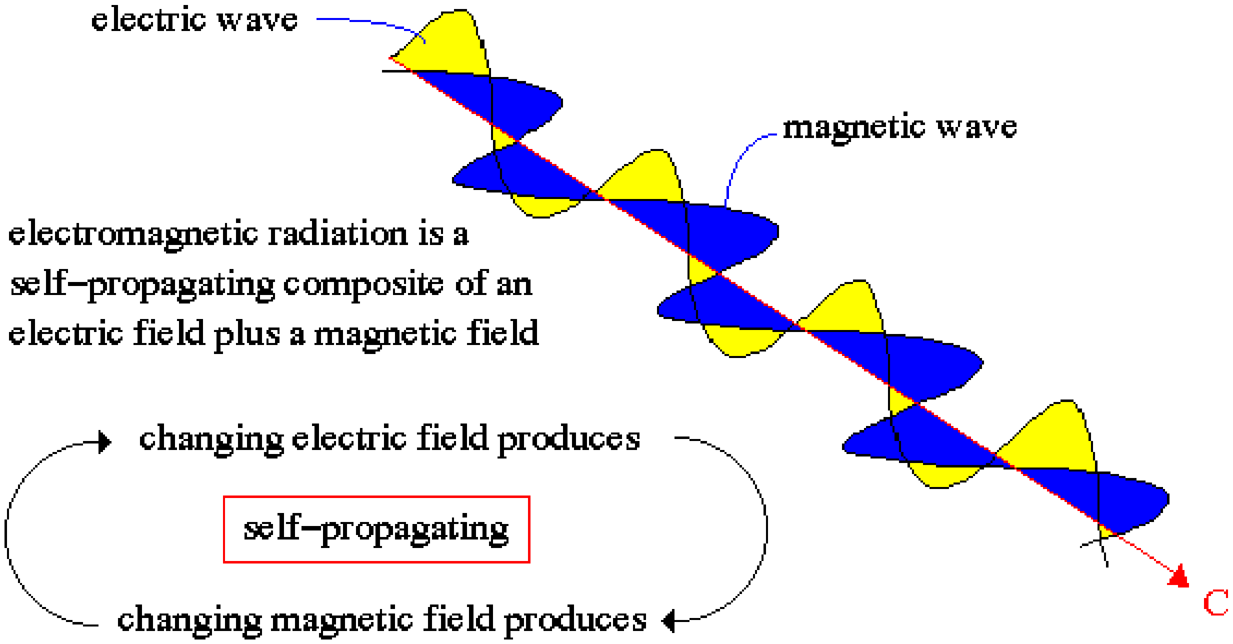
Although conceived of as distinct phenomena until the 19th century, electricity

and magnetism are now known to be components of the unified theory of electromagnetism.

A connection between electricity and magnetism had long been suspected, and in 1820 the Danish physicist Hans Christian Orsted showed that an electric current flowing in a wire produces its own magnetic field. Andre-Marie Ampere of France immediately repeated Orsted's experiments and within weeks was able to express the magnetic forces between current-carrying conductors in a simple and elegant mathematical form. He also demonstrated that a current flowing in a loop of wire produces a magnetic dipole indistinguishable at a distance from that produced by a small permanent magnet; this led Ampere to suggest that magnetism is caused by currents circulating on a molecular scale, an idea remarkably near the modern understanding.

Faraday, in the early 1800's, showed that a changing electric field produces a magnetic field, and that vice-versus, a changing magnetic field produces an electric current. An electromagnet is an iron core which enhances the magnetic field generated by a current flowing through a coil, was invented by William Sturgeon in England during the mid-1820s. It later became a vital component of both motors and generators.

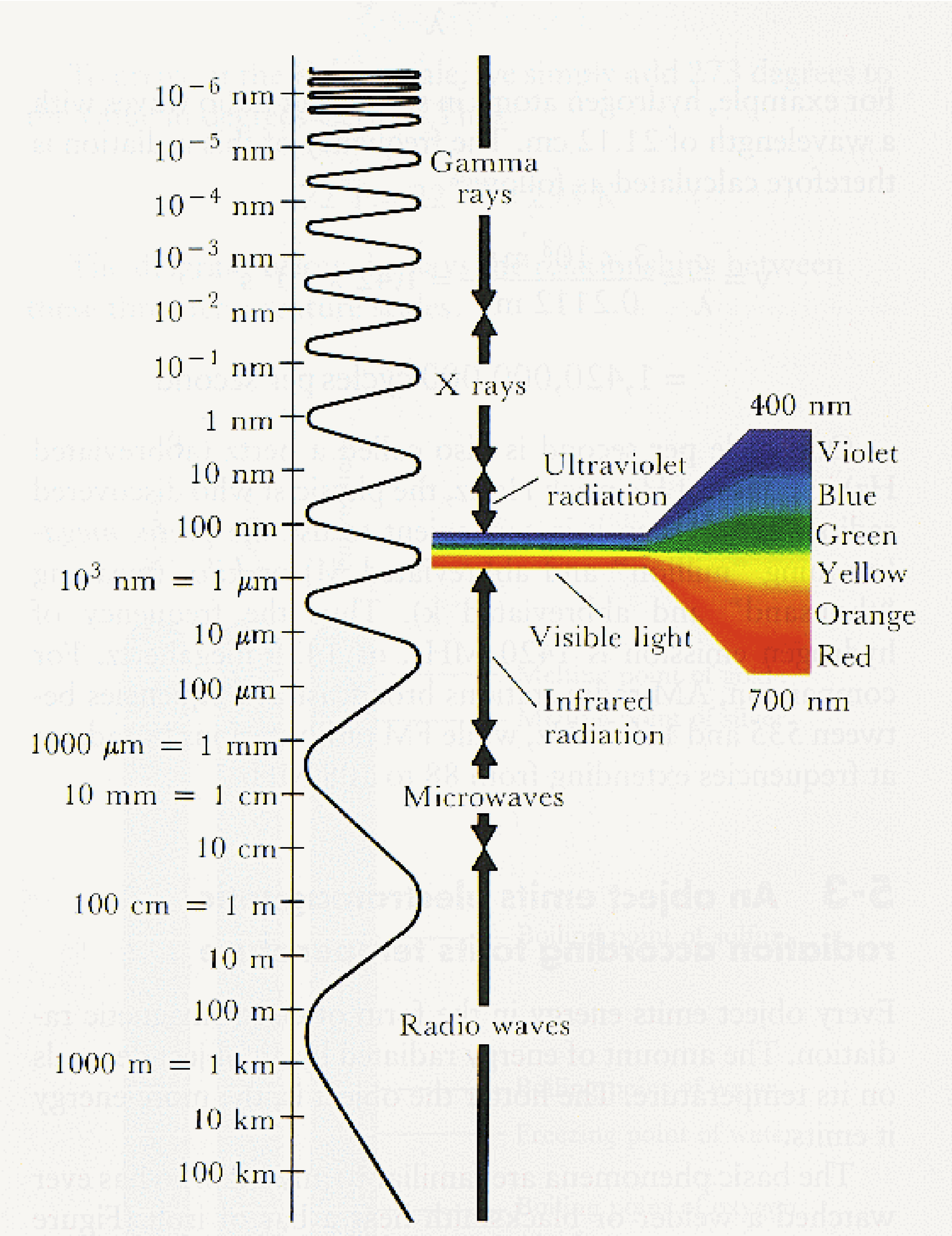
The unification of electric and magnetic phenomena in a complete mathematical theory was the achievement of the Scottish physicist Maxwell (1850's). In a set of four elegant equations, Maxwell formalized the relationship between electric and magnetic fields. In addition, he showed that a linear magnetic and electric field can be self-reinforcing and must move at a particular velocity, the speed of light. Thus, he concluded that light is energy carried in the form of opposite but supporting electric and magnetic fields in the shape of waves, i.e. self-propagating electromagnetic waves.



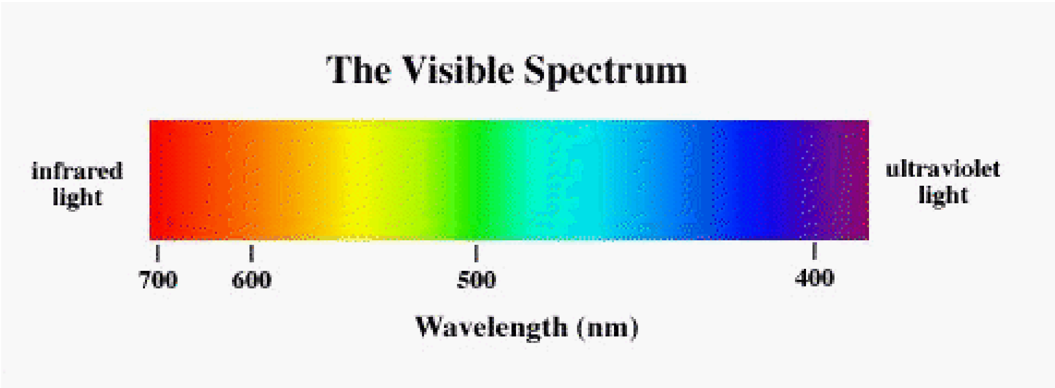

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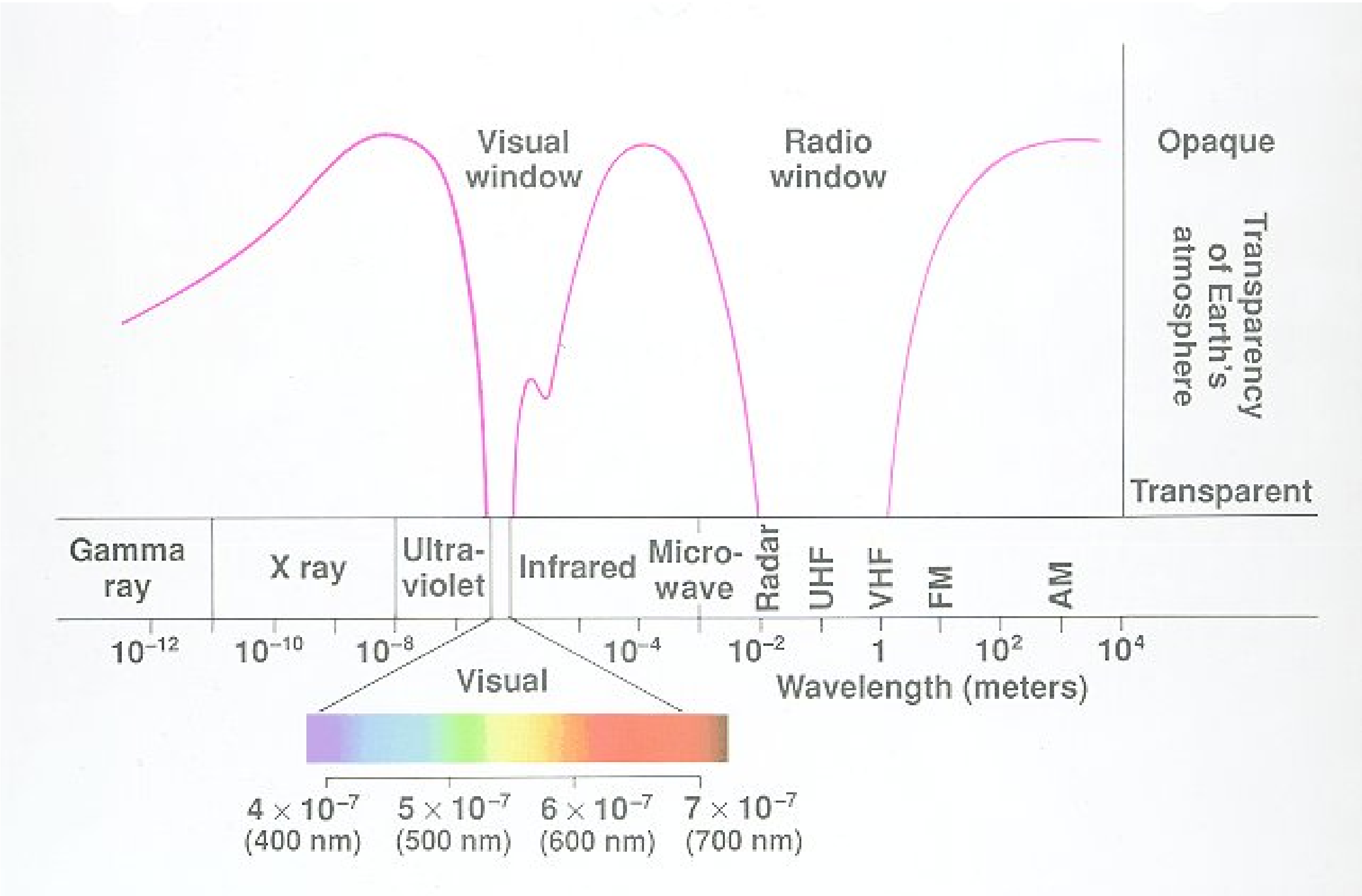
Electromagnetic Radiation (a.k.a. Light):

The wavelength of the light determines its characteristics. For example, short wavelengths are high energy gamma-rays and x-rays, long wavelengths are radio waves. The whole range of wavelengths is called the electromagnetic spectrum.




Our eyes only see over the following range of wavelengths:



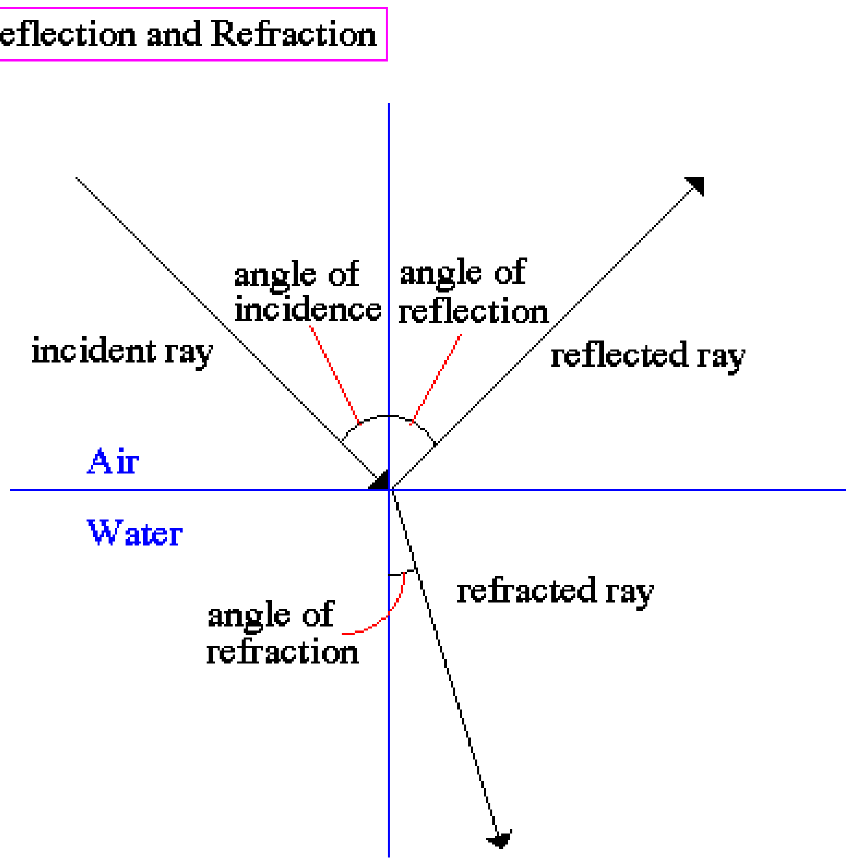

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Wave Properties:

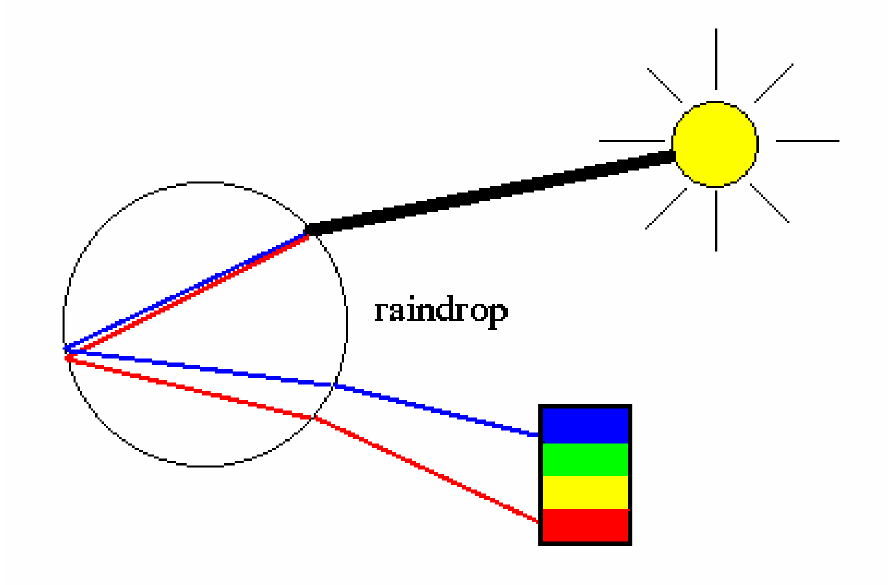
Due to its wave-like nature, light has three properties when encountering a medium:

1) reflection
2) refraction
3) diffraction

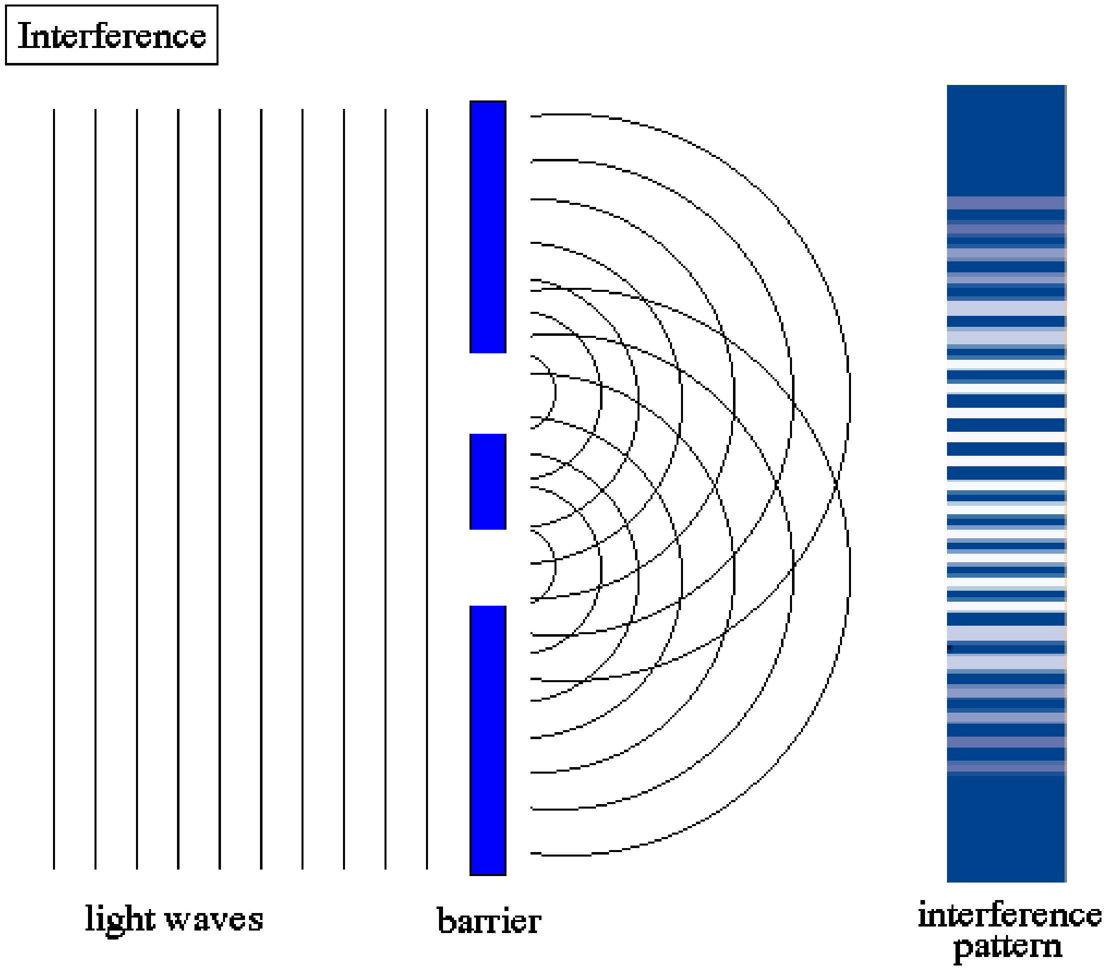
When a light ray strikes a medium, such as oil or water, the ray is both refracted and reflected as shown below:




The angle of refraction is greater for a denser medium and is also a function of wavelength (i.e. blue light is more refracted compared to red and this is the origin to rainbows from drops of water)




Diffraction is the constructive and destructive interference of two beams of light that results in a wave-like pattern

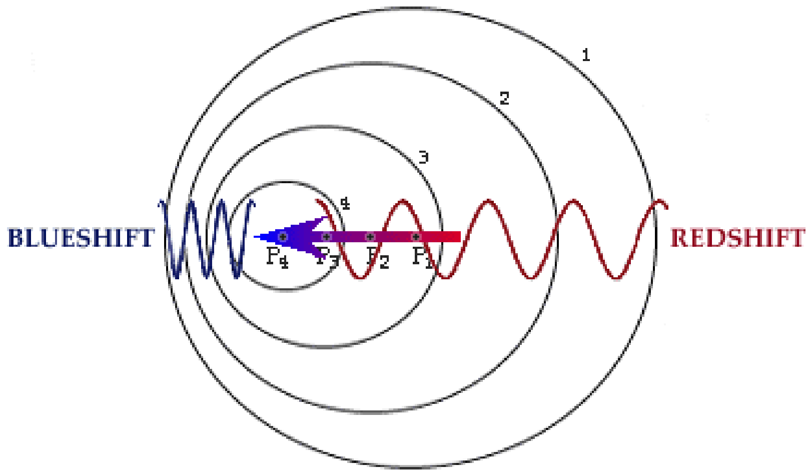



[click here to see interference movie]

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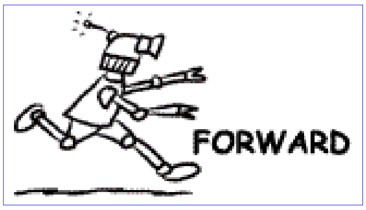
Doppler effect:

The Doppler effect occurs when on object that is emitting light is in motion with respect to the observer. The speed of light does not change, only the wavelength. If the object is moving towards the observer the light is ``compressed" or blueshifted. If the object is moving away from the observer the light is ``expanded" or redshifted.



We can use the Doppler effect to measure the orbital velocity of planets and the rotation of the planets.

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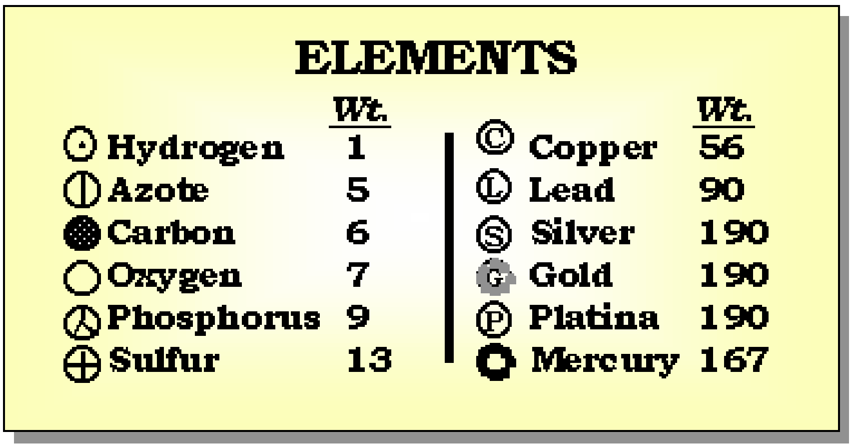



Atomic Theory:

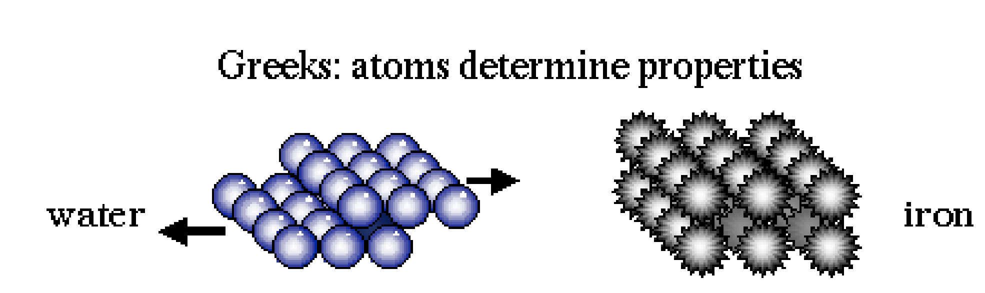
The ancient philosopher, Heraclitus, maintained that everything is in a state of flux. Nothing escapes change of some sort (it is impossible to step into the same river). On the other hand, Parmenides argued that everything is what it is, so that it cannot become what is not (change is impossible because a substance would have to transition through nothing to become something else, which is a logical contradiction). Thus, change is incompatible with being so that only the permanent aspects of the Universe could be considered real.

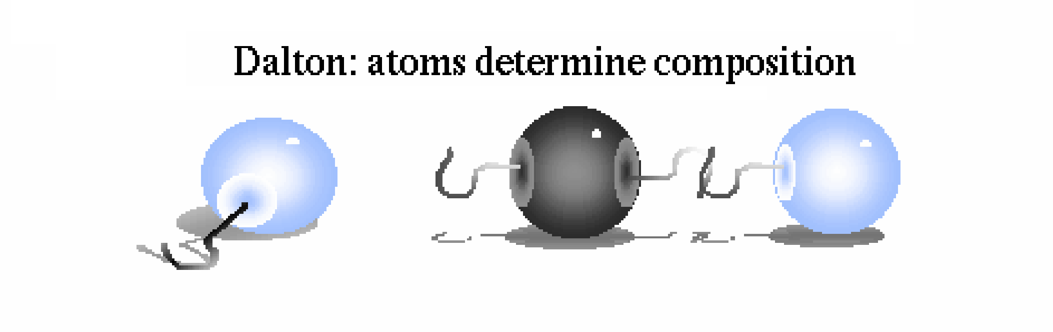
An ingenious escape was proposed in the fifth century B.C. by Democritus. He hypothesized that all matter is composed of tiny indestructible units, called atoms. The atoms themselves remain unchanged, but move about in space to combine in various ways to form all macroscopic objects. Early atomic theory stated that the characteristics of an object are determined by the shape of its atoms. So, for example, sweet things are made of smooth atoms, bitter things are made of sharp atoms.

In this manner permanence and flux are reconciled and the field of atomic physics was born. Although Democritus' ideas were to solve a philosophical dilemma, the fact that there is some underlying, elemental substance to the Universe is a primary driver in modern physics, the search for the ultimate subatomic particle.




It was John Dalton, in the early 1800's, who determined that each chemical element is composed of a unique type of atom, and that the atoms differed by their masses. He devised a system of chemical symbols and, having ascertained the relative weights of atoms, arranged them into a table. In addition, he formulated the theory that a chemical combination of different elements occurs in simple numerical ratios by weight, which led to the development of the laws of definite and multiple proportions.



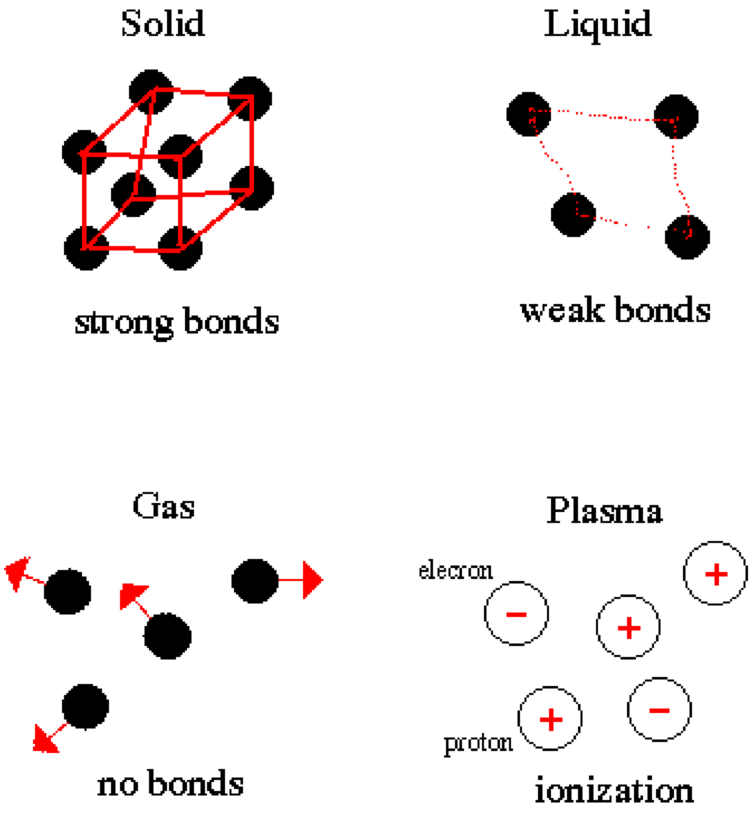

He then determined that compounds are made of molecules, and that molecules are composed of atoms in definite proportions. Thus, atoms determine the composition of matter, and compounds can be broken down into their individual elements.

The first estimates for the sizes of atoms and the number of atoms per unit volume where made by Joesph Loschmidt in 1865. Using the ideas of kinetic theory, the idea that the properties of a gas are due to the motion of the atoms that compose it, Loschmidt calculated the mean free path of an atom based on diffusion rates. His result was that there are $6.022 \times 10^{23}$ atoms per 12 grams of carbon. And that the typical diameters of an atom is $10^{-8}$ centimeters.

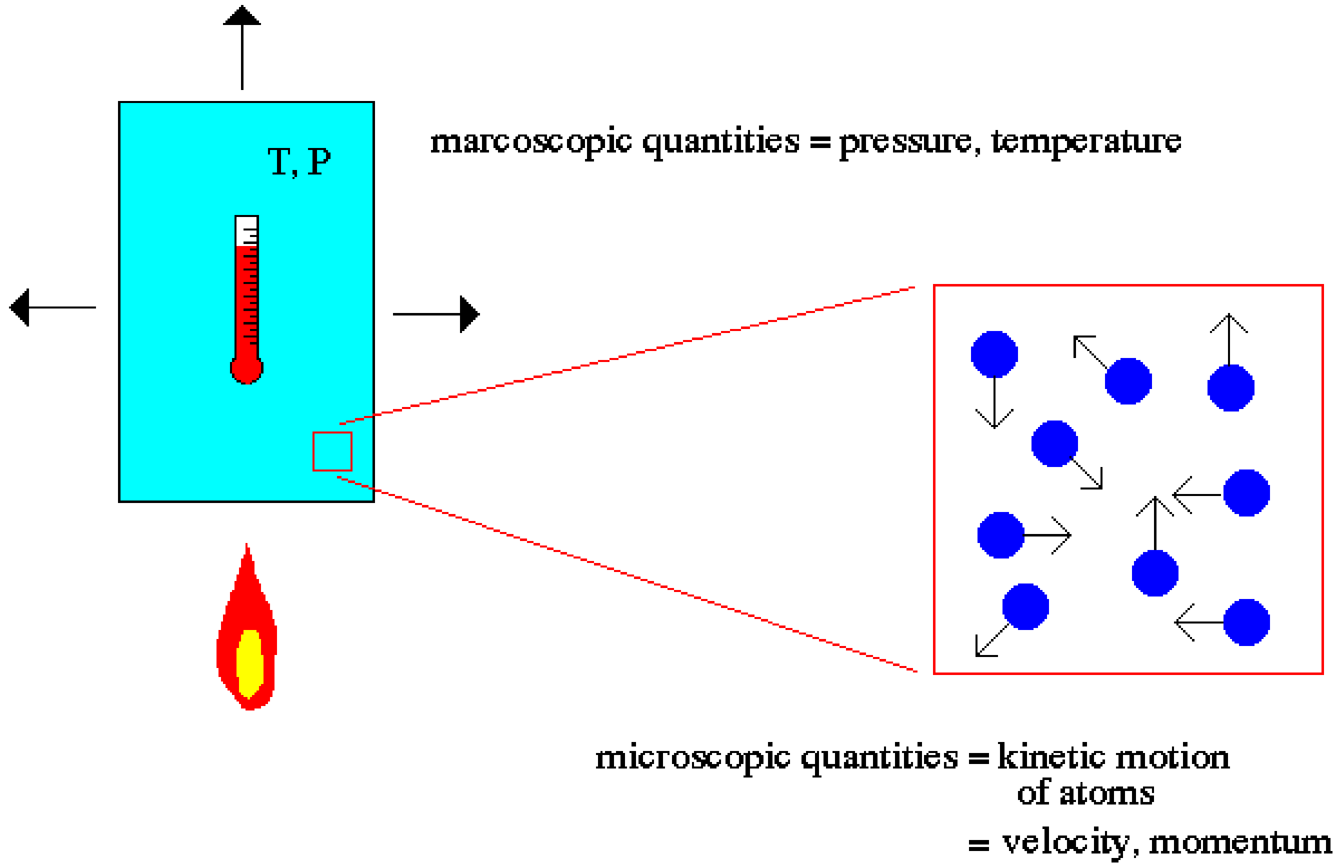
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Matter:

Matter exists in four states: solid, liquid, gas and plasma. Plasmas are only found in the coronae and cores of stars. The state of matter is determined by the strength of the bonds between the atoms that makes up matter. Thus, is proportional to the temperature or the amount of energy contained by the matter.




The change from one state of matter to another is called a phase transition. For example, ice (solid water) converts (melts) into liquid water as energy is added. Continue adding energy and the water boils to steam (gaseous water) then, at several million degrees, breaks down into its component atoms.




The key point to note about atomic theory is the relationship between the macroscopic world (us) and the microscopic world of atoms. For example, the macroscopic world deals with concepts such as temperature and pressure to describe matter. The microscopic world of atomic theory deals with the kinetic motion of atoms to explain macroscopic quantities.

Temperature is explained in atomic theory as the motion of the atoms (faster = hotter). Pressure is explained as the momentum transfer of those moving atoms on the walls of the container (faster atoms = higher temperature = more momentum/hits = higher pressure).

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Ideal Gas Law:

Macroscopic properties of matter are governed by the Ideal Gas Law of chemistry.

An ideal gas is a gas that conforms, in physical behavior, to a particular, idealized relation between pressure, volume, and temperature. The ideal gas law states that for a specified quantity of gas, the product of the volume, V, and pressure, P, is proportional to the absolute temperature T; i.e., in equation form, PV = kT, in which k is a constant. Such a relation for a substance is called its equation of state and is sufficient to describe its gross behavior.

Although no gas is perfectly described by the above law, the behavior of real gases is

described quite closely by the ideal gas law at sufficiently high temperatures and low pressures (such as air pressure at sea level), when relatively large distances between molecules and their high speeds overcome any interaction. A gas does not obey the equation when conditions are such that the gas, or any of the component gases in a mixture, is near its triple point.

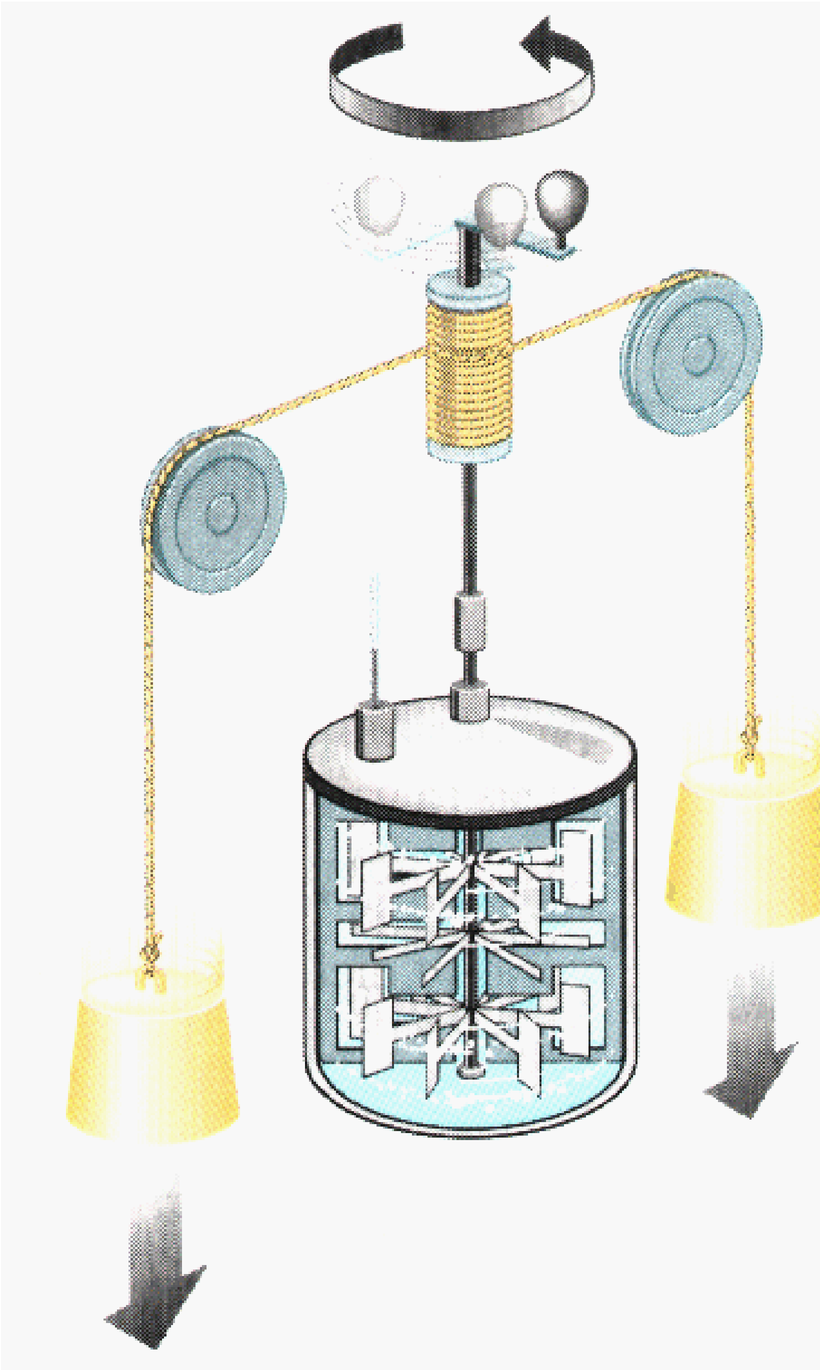
The ideal gas law can be derived from the kinetic theory of gases and relies on the assumptions that (1) the gas consists of a large number of molecules, which are in random motion and obey Newton's deterministic laws of motion; (2) the volume of the molecules is negligibly small compared to the volume occupied by the gas; and (3) no forces act on the molecules except during elastic collisions of negligible duration.

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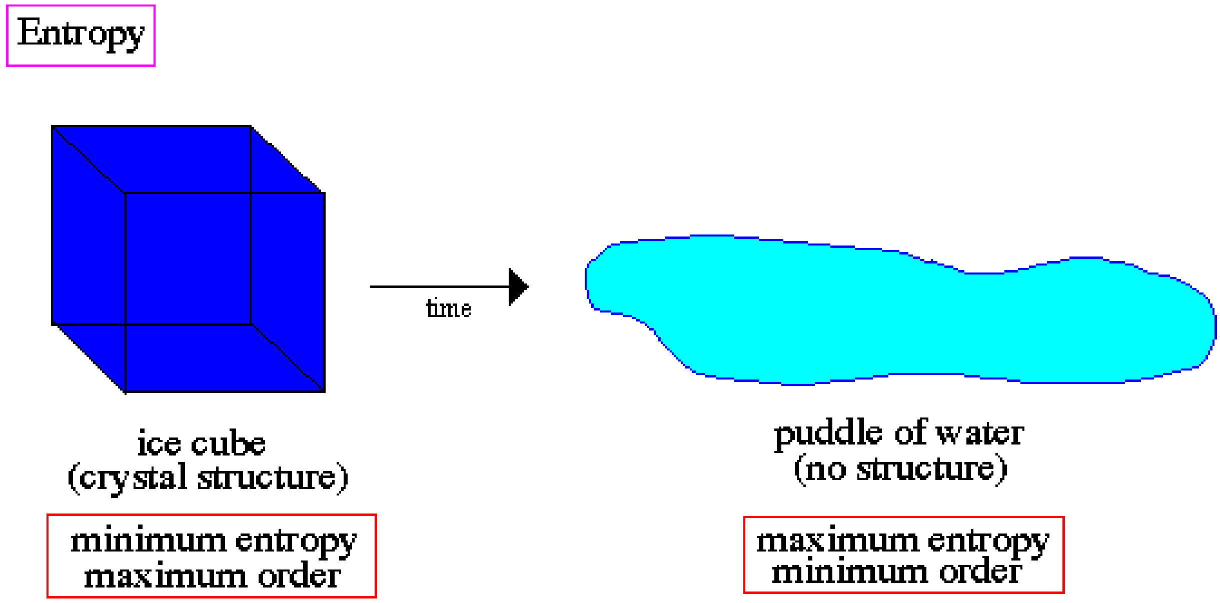
Thermodynamics:

The study of the relationship between heat, work, temperature, and energy, encompassing the general behavior of physical system is called thermodynamics.

The first law of thermodynamics is often called the law of the conservation of energy (actually mass-energy) because it says, in effect, that when a system undergoes a process, the sum of all the energy transferred across the system boundary--either as heat or as work--is equal to the net change in the energy of the system. For example, if you perform physical work on a system (e.g. stir some water), some of the energy goes into motion, the rest goes into raising the temperature of the system.



The second law of thermodynamics states that, in a closed system, the entropy increases. Cars rust, dead trees decay, buildings collapse; all these things are examples of entropy in action, the spontaneous movement from order to disorder.




Classical or Newtonian physics is incomplete because it does not include irreversible processes associated with the increase of entropy. The entropy of the whole Universe always increased with time. We are simply a local spot of low entropy and our destiny is linked to the unstoppable increase of disorder in our world => stars will burn out, civilizations will die from lack of power.

The approach to equilibrium is therefore an irreversible process. The tendency toward equilibrium is so fundamental to physics that the second law is probably the most universal regulator of natural activity known to science.

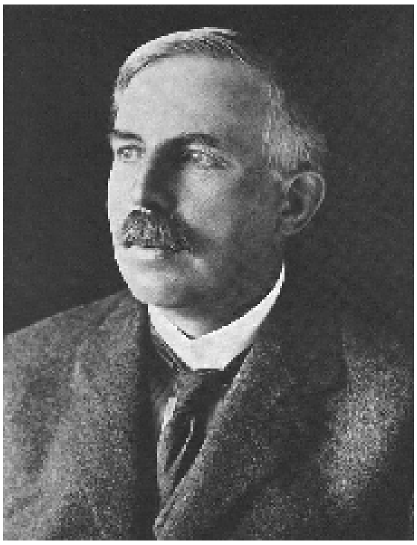
The concept of temperature enters into thermodynamics as a precise mathematical quantity that relates heat to entropy. The interplay of these three quantities is further constrained by the third law of thermodynamics, which deals with the absolute zero of temperature and its theoretical unattainability.

Absolute zero (approximately -273 C) would correspond to a condition in which a system had achieved its lowest energy state. The third law states that, as this minimum temperature is approached, the further extraction of energy becomes more and more difficult.

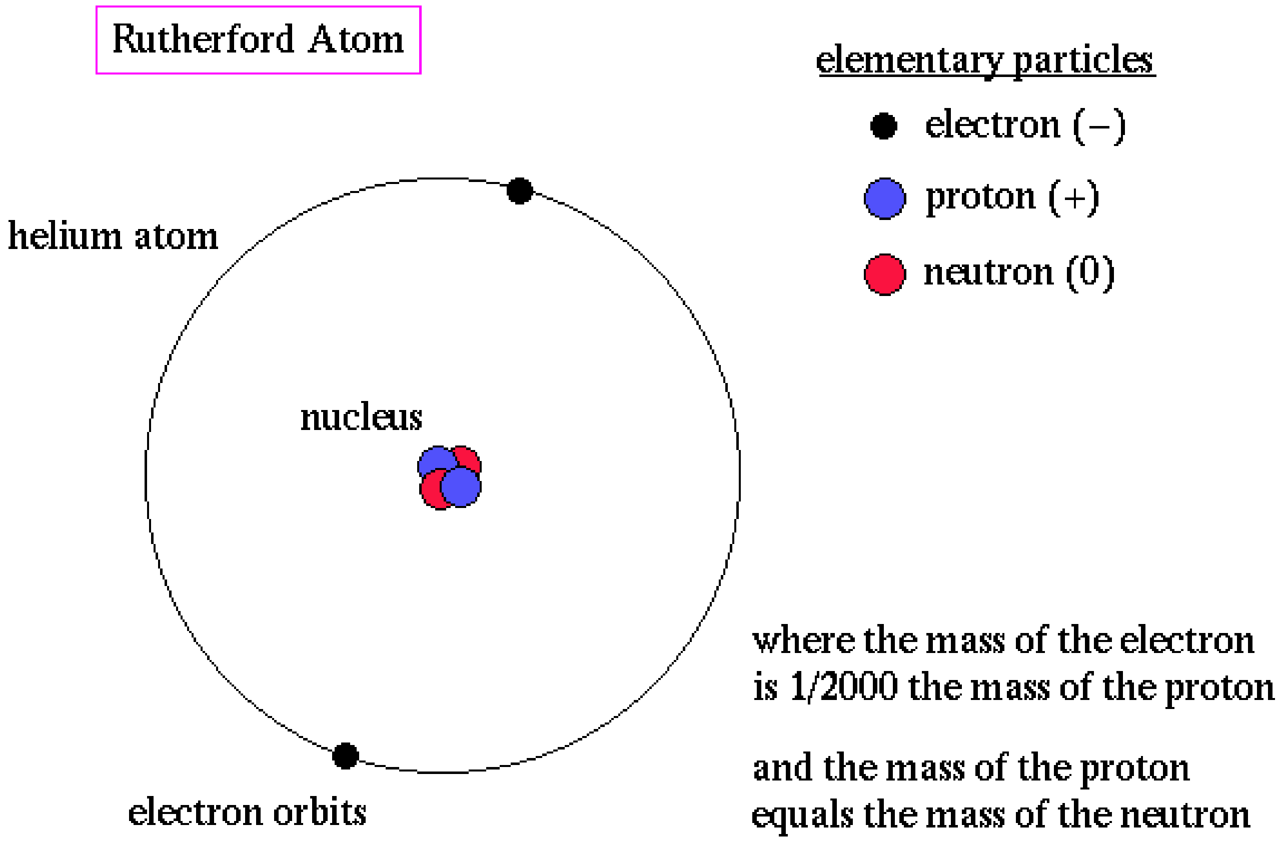
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Rutherford Atom:

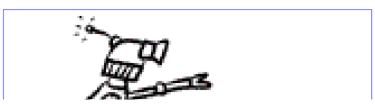
Ernest Rutherford is considered the father of nuclear physics. Indeed, it could be said that Rutherford invented the very language to describe the theoretical concepts of the atom and the phenomenon of radioactivity. Particles named and characterized by him include the alpha particle, beta particle and proton. Rutherford overturned Thomson's atom model in 1911 with his well-known gold foil experiment in which he demonstrated that the atom has a tiny, massive nucleus.



His results can best explained by a model for the atom as a tiny, dense, positively charged core called a nucleus, in which nearly all the mass is concentrated, around which the light, negative constituents, called electrons, circulate at some distance, much like planets revolving around the Sun.




The Rutherford atomic model has been alternatively called the nuclear atom, or the planetary model of the atom.





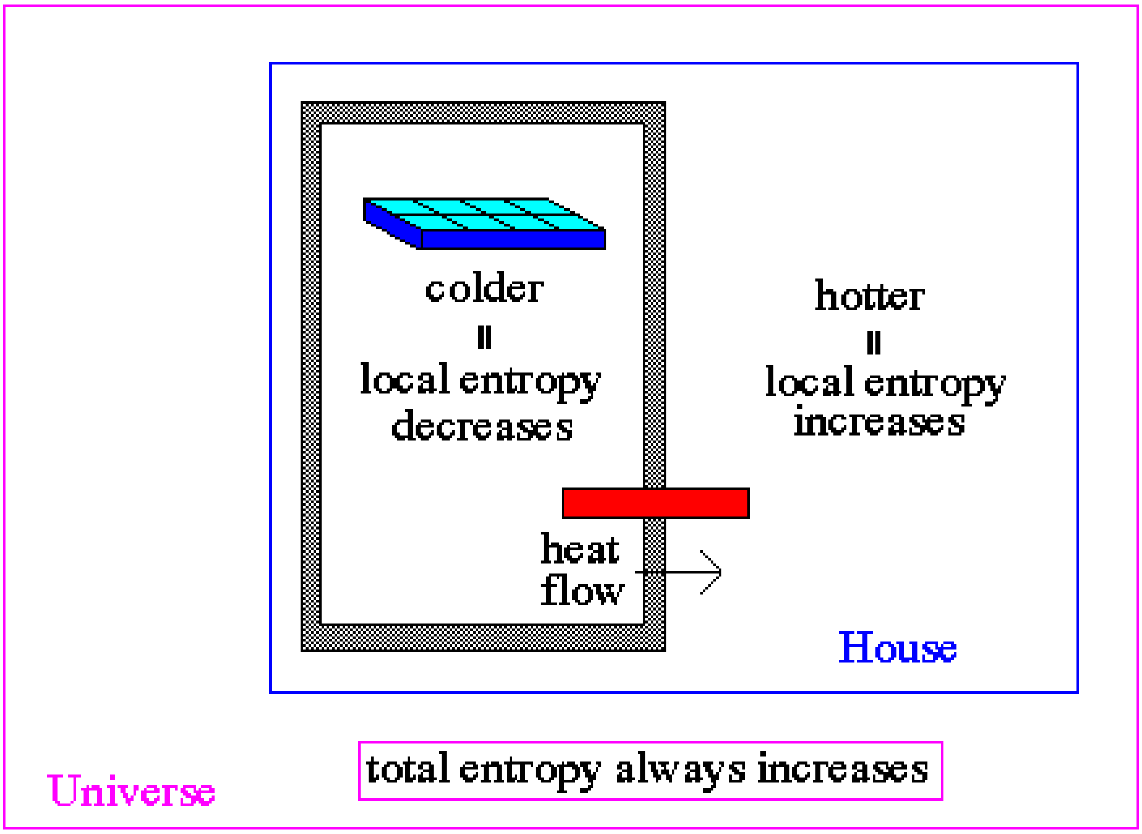

FORWARD



Entropy:

Cars rust, dead trees decay, buildings collapse; all these things are examples of entropy in action, the spontaneous and continuous movement from order to disorder.

The measure of entropy must be global. For example, you can pump heat out of a refrigerator (to make ice cubes), but the heat is placed in the house and the entropy of the house increases, even though the local entropy of the ice cube tray decreases. So the sum of the entropy in the house and refrigerator increases.




The concept of entropy applies to many other physical systems other than heat. For example, information flow suffers from entropy. A signal is always degraded by random noise.

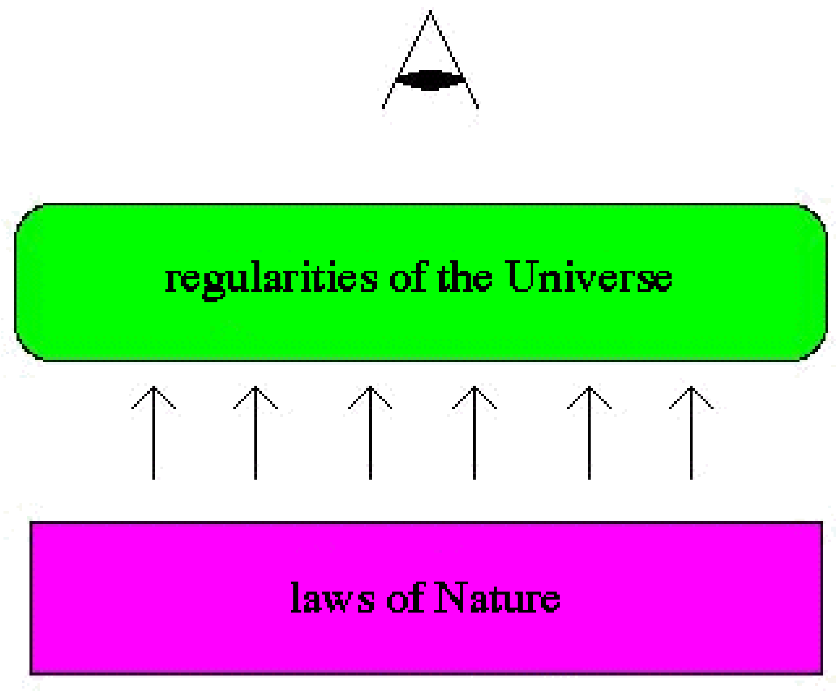
The entropy of the whole Universe always increased with time. We are simply a local spot of low entropy and our destiny is linked to the unstoppable increase of disorder in our world => stars will burn out, civilizations will die from lack of power.

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Irreversibility:

Classical physics is a science upon which our belief in a deterministic, time-reversible description of Nature is based. Classical physics does not include any distinction between the past and the future. The Universe is ruled by deterministic laws, yet the macroscopic world is not reversible. This is known as Epicurus' clinamen, the dilemma of being and becoming, the idea that some element of chance is needed to account for the deviation of material motion from rigid predetermined evolution.

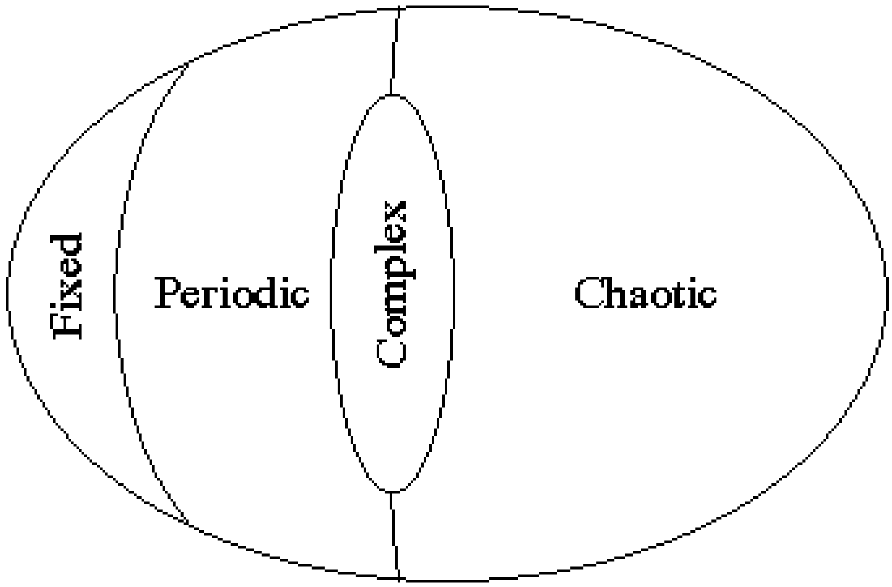
The astonishing success of simple physical principles and mathematical rules in explaining large parts of Nature is not something obvious from our everyday experience. On casual inspection, Nature seems extremely complex and random. There are few natural phenomenon which display the precise sort of regularity that might hint of an underlying order. Where trends and rhythms are apparent, they are usually of an approximate and qualitative form. How are we to reconcile these seemingly random acts with the supposed underlying lawfulness of the Universe?



For example, consider falling objects. Galileo realized that all bodies accelerate at the same rate regardless of their size or mass. Everyday experience tells you differently because a feather falls slower than a cannonball. Galileo's genius lay in spotting that the differences that occur in the everyday world are in incidental complication (in this case, air friction) and are irrelevant to the real underlying properties (that is, gravity). He was able to abstract from the complexity of real-life situations the simplicity of an idealized law of gravity. Reversible processes appear to be idealizations of real processes in Nature.

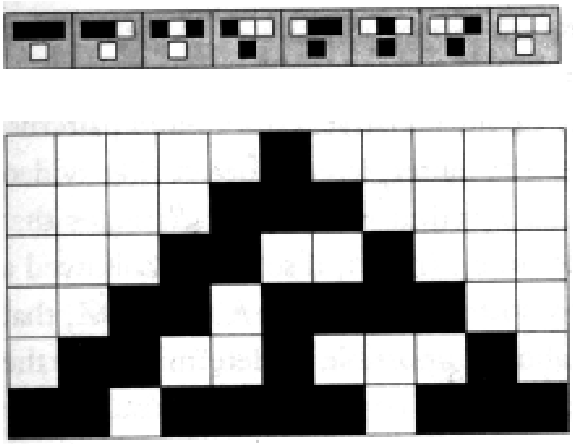
Probability-based interpretations make the macroscopic character of our observations responsible for the irreversibility that we observe. If we could follow an individual molecule we would see a time reversible system in which the each molecule follows the laws of Newtonian physics. Because we can only describe the number of molecules in each compartment, we conclude that the system evolves towards equilibrium. Is irreversibility merely a consequence of the approximate macroscopic character of our observations? Is it due to our own ignorance of all the positions and velocities?

Irreversibility leads to both order and disorder. Nonequilibrium leads to concepts such as self-organization and dissipative structures (Spatiotemporal structures that appear in far-from-equilibrium conditions, such as oscillating chemical reactions or regular spatial structures, like snowflakes). Objects far from equilibrium are highly organized thanks to temporal, irreversible, nonequilibrium processes (like a pendulum).



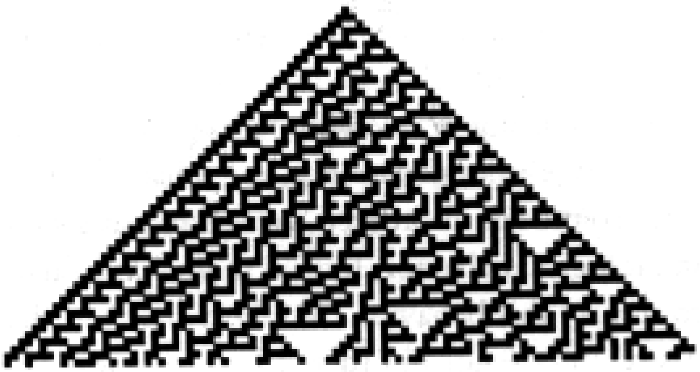

Information movement in complex dynamical systems is such that the regime at the left is where information is frozen, to the right is a flexible regime where behavior such as crystal growth is found. To the far right, information moves so freely that its structure cannot be maintained; the regime is too chaotic. Only in the center region can information be stable enough to support message structure.

The behavior of complex systems is not truly random, it is just that the final state is so sensitive to the initial conditions that it is impossible to predict the future behavior without infinite knowledge of all the motions and energy (i.e. a butterfly in South America influences storms in the North Atlantic).

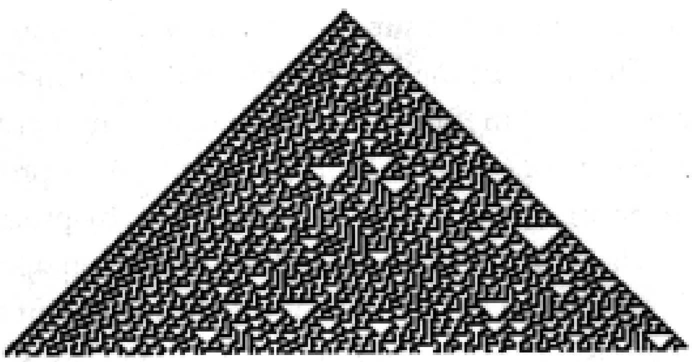


5 generations

*The growth of a two-state (on or off) one-dimensional cellular automaton. The row of eight boxes on top shows the rule set: for each combination of three cells in generation 0, there is a determined result for the next-generation cell below the triplet. Beginning from a single seed, these rules are applied consistently, each generation represented by a horizontal row of cells. The first image shows five generations of growth, the second image shows fifty, and the third shows 100 generations, by which time it is clear that simple rules have generated considerable complexity.*



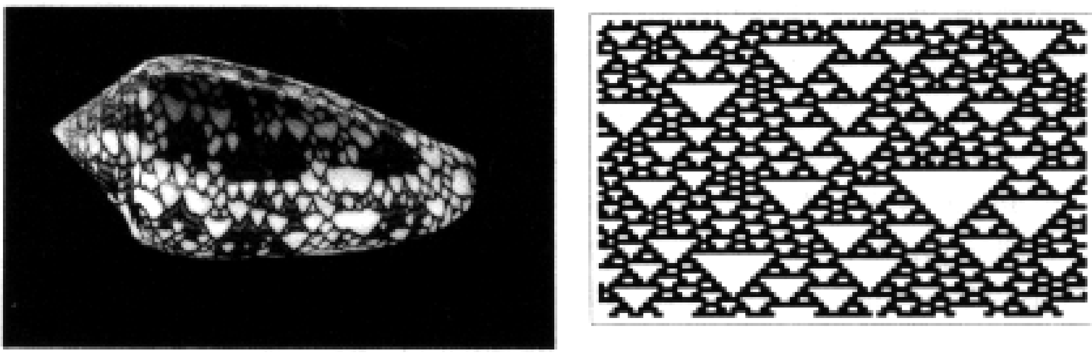
50 generations



100 generations

Although this is `just' a mathematical game, there are many examples of the same shape and complex behavior occurring in Nature.

*A comparison between the natural pattern on a mollusk shell and the pattern of a simple one-dimensional cellular automaton.*



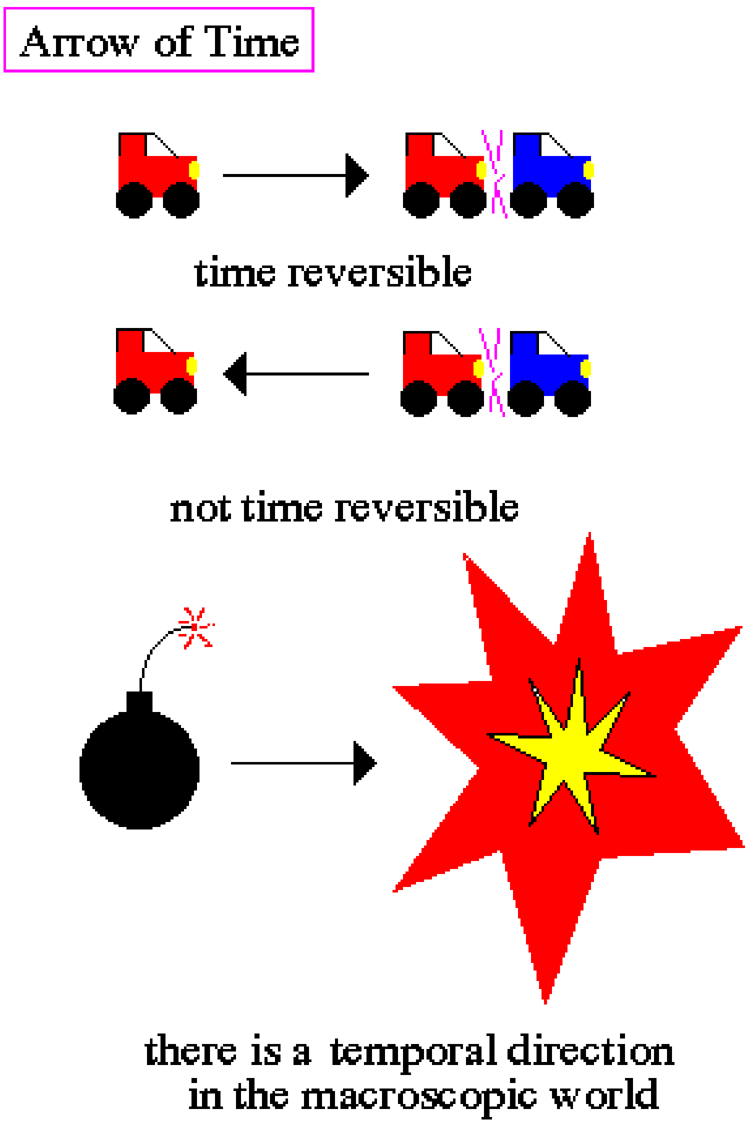
Individual descriptions are called trajectories, statistical descriptions of groups are called ensembles. Individual particles are highly deterministic, trajectories are fixed. Yet ensembles of particles follow probable patterns and are uncertain. Does this come from ignorance of all the trajectories or something deeper in the laws of Nature? Any predictive computation will necessarily contain some input errors because we cannot measure physical quantities to unlimited precision.

Note that relative probabilities evolve in a deterministic manner. A statistical theory can remain deterministic. However, macroscopic irreversibility is the manifestation of the randomness of probabilistic processes on a microscopic scale. Success of reductionism was based on the fact that most simple physical systems are linear, the whole is the sum of the parts. Complexity arrives in nonlinear systems.

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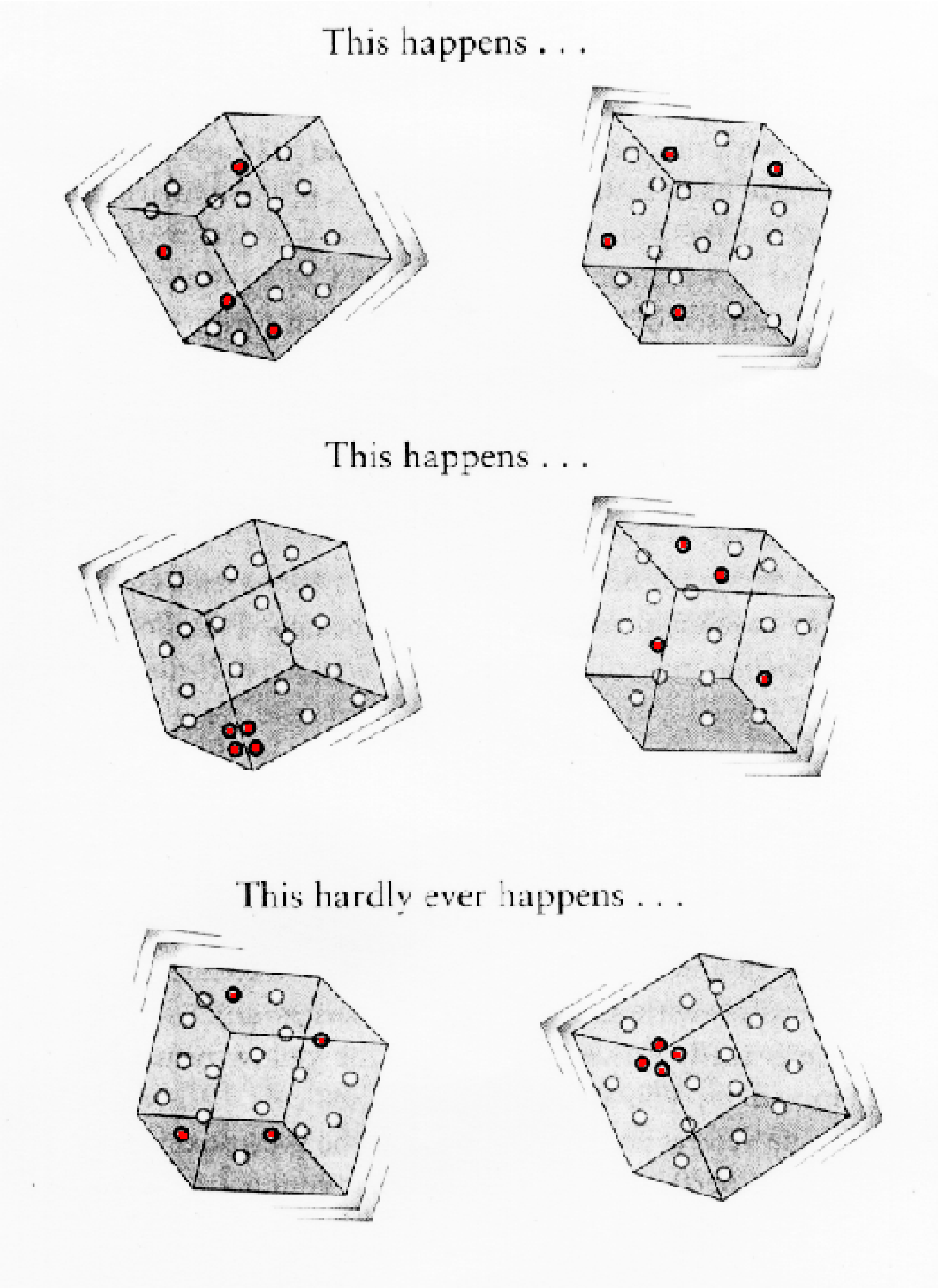
Arrow of Time:

Why do we perceive time as always moving forward? Why are our memories always of the past and never of the future? All the fundamental Newtonian laws are time reversible. Collisions look the same forwards or backwards. A box of gas molecules obeying Newton's laws perfectly does not have an inbuilt arrow of time. However, it is possible to show that the continual random molecular motions will cause the entire ensemble to visit and revisit every possible state of the box, much like the continual shuffling of a deck of cards will eventually reproduce any sequence.




This ability of Nature to be divided into a multitude of states makes it easier to understand why thermodynamical systems move toward equilibrium, known as Poincare's theorem. If a box of gas is in a low entropy state at one moment, it will very probably soon be in a less ordered state since given the large number of states for it to evolve to, most of those states are of higher entropy. So just by the laws of chance, the box has a higher probability of becoming a higher entropy state rather than a lower one since there are so many more possible high entropy states.

Poincare's theorem claims that if every individual state has the same chance of being visited, then obviously mixed-up states are going to turn up much more often than the less mixed-up or perfectly ordered states, simply because there are many more of them.

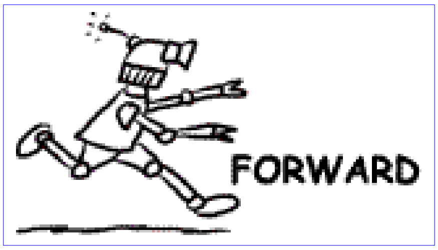



Thermodynamical events, such as a growing tree, are not reversible. Cracked eggs do not repair themselves. Defined by these events, time

has an arrow, a preferred direction.

Entropy and the arrow of time are strongly linked. Increasing entropy is in the direction of positive time. However, a study of the components to systems shows that the parts are describable in terms of time-symmetric laws. In other words, the microscopic world is ruled by time-symmetric laws, but the macroscopic world has a particular direction.

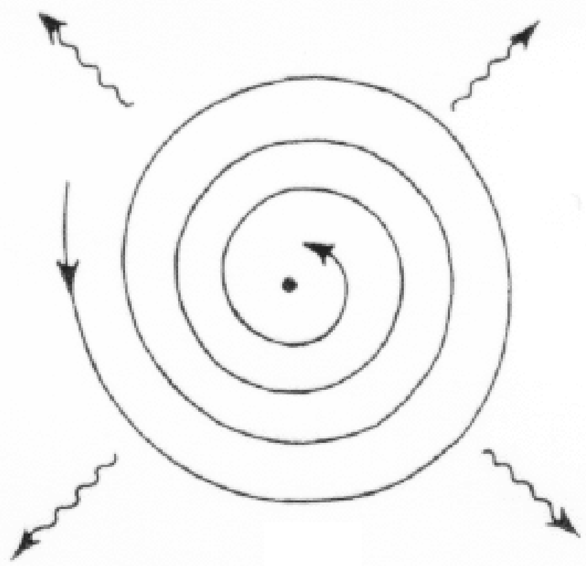
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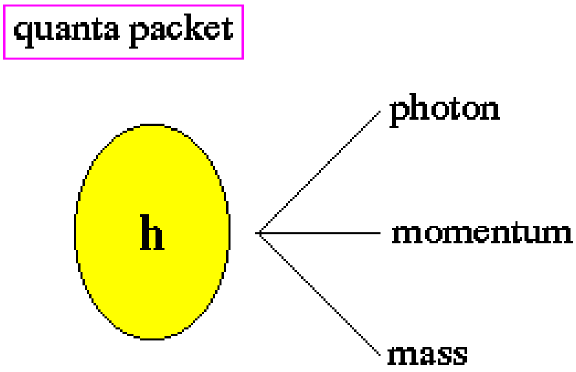

Planck's constant:

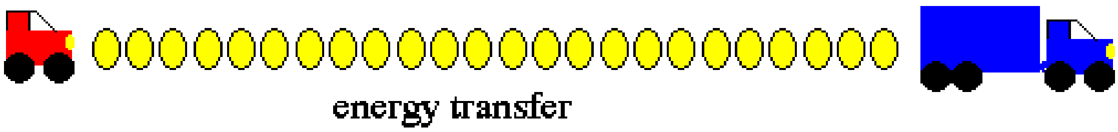
In the early 1900's, German physicist E. Planck noticed fatal flaw in our physics by demonstrating that the electron in orbit around the nucleus accelerates. Acceleration means a changing electric field (the electron has charge), when means photons should be emitted. But, then the electron would lose energy and fall into the nucleus. Therefore, atoms shouldn't exist!



According to classical physics, an electron in orbit around an atomic nucleus should emit electronmagnetic radiation (photons) continuously, because it is continually accelerating in a curved path. The resulting loss of energy implies that the electron should spiral into the nucleus in a very short time (i.e. atoms can not exist).

To resolve this problem, Planck made a wild assumption that energy, at the sub-atomic level, can only be transfered in small units, called quanta. Due to his insight, we call this unit Planck's constant (h). The word quantum derives from quantity and refers to a small packet of action or process, the smallest unit of either that can be associated with a single event in the microscopic world.




Changes of energy, such as the transition of an electron from one orbit to another around the nucleus of an atom, is done in discrete quanta. Quanta are not divisible and the term quantum leap refers to the abrupt movement from one discrete energy level to another, with no smooth transition. There is no ``inbetween''.

The quantization, or ``jumpiness'' of action as depicted in quantum physics differs sharply from classical physics which represented motion as smooth, continuous change. Quantization limits the energy to be transfered to photons and resolves the UV catastrophe problem.

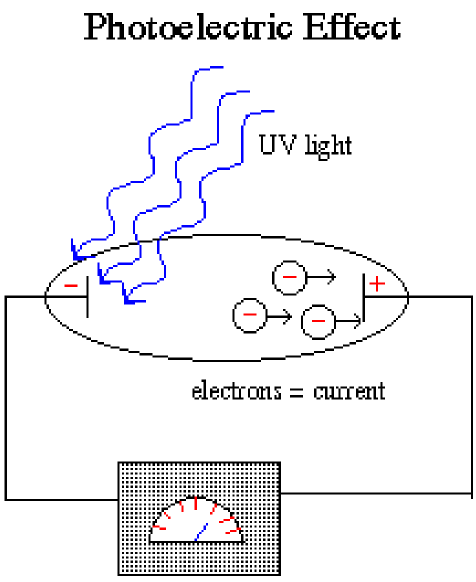
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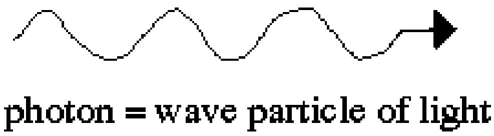
Wave-Particle Dualism:

The wave-like nature of light explains most of its properties:

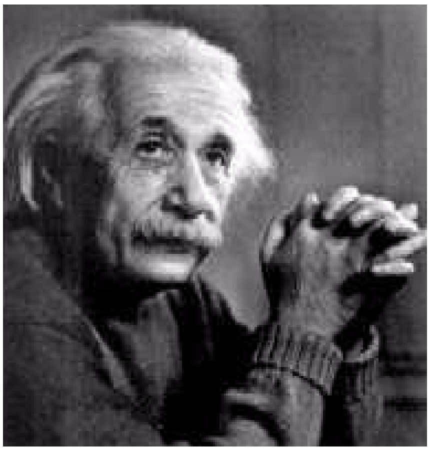
- reflection/refraction
- diffraction/interference
- Doppler effect

But, the results from stellar spectroscopy (emission and absorption spectra) can only be explained if light has a particle nature as shown by Bohr's atom and the photon description of light.




This dualism to the nature of light is best demonstrated by the photoelectric effect, where a weak UV light produces a current flow (releases electrons) but a strong red light does not release electrons no matter how intense the red light.



Einstein explained the photoelectric effect by assuming that light exists in a particle-like state, packets of energy (quanta) called photons. There is no current flow for red light because the packets of energy carried by each individual red photons are too weak to knock the electrons off the atoms no matter how many red photons you beamed onto the cathode. But the individual UV photons were each strong enough to release the electron and cause a current flow.

It is one of the strange, but fundamental, concepts in modern physics that light has both a wave and particle state (but not at the same time), called wave-particle dualism.

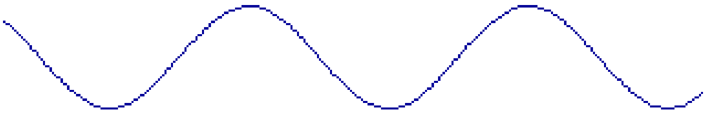
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de Broglie Matter Waves:

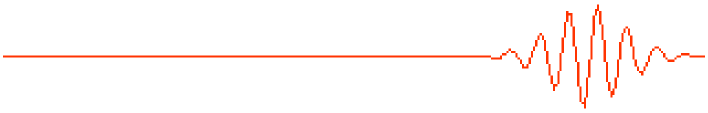
Perhaps one of the key questions when Einstein offered his photon description of light is, does an electron have wave-like properties? The response to this question arrived from the Ph.D. thesis of Louis de Broglie in 1923. de Broglie argued that since light can display wave and particle properties, then matter can also be a particle and a wave too.



One way of thinking of a matter wave (or a photon) is to think of a wave packet. Normal waves look with this:



having no beginning and no end. A composition of several waves of different wavelength can produce a wave packet that looks like this:



So a photon, or a free moving electron, can be thought of as a wave packet, having both wave-like properties and also the single position and size we associate with a particle. There are some slight problems, such as the wave packet doesn't really stop at a finite distance from its peak, it also goes on for every and every. Does this mean an electron exists at all places in its trajectory?

de Broglie also produced a simple formula that the wavelength of a matter particle is related to the momentum of the particle. So energy is also connected to the wave

property of matter.

While de Broglie waves were difficult to accept after centuries of thinking of particles are solid things with definite size and positions, electron waves were confirmed in the laboratory by running electron beams through slits and demonstrating that interference patterns formed.

How does the de Broglie idea fit into the macroscopic world? The length of the wave diminishes in proportion to the momentum of the object. So the greater the mass of the object involved, the shorter the waves. The wavelength of a person, for example, is only one millionth of a centimeter, much to short to be measured. This is why people don't `tunnel' through chairs when they sit down.

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Uncertainty Principle:

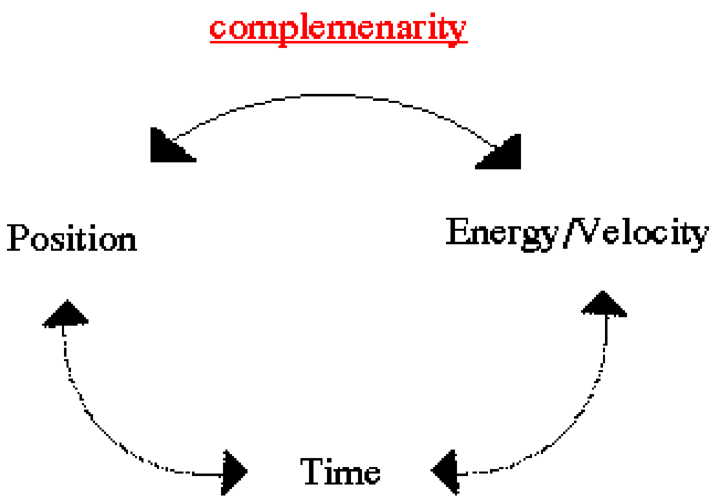
Classical physics was on loose footing with problems of wave/particle duality, but was caught completely off-guard with the discovery of the uncertainty principle.



The uncertainty principle, developed by W. Heisenberg, is a statement of the effects of wave-particle duality on the properties of subatomic objects. Consider the concept of momentum in the wave-like microscopic world. The momentum of wave is given by its wavelength. A wave packet like a photon or electron is a composite of many waves. Therefore, it must be made of many momentums. But how can an object have many momentums?

Of course, once a measurement of the particle is made, a single momentum is observed. But, like fuzzy position, momentum before the observation is intrinsically uncertain. This is what is know as the uncertainty principle, that certain quantities, such as position, energy and time, are unknown, except by probabilities. In its purest form, the uncertainty principle states that accurate knowledge of complementarity pairs is

impossible. For example, you can measure the location of an electron, but not its momentum (energy) at the same time.




Mathematically we describe the uncertainty principle as the following, where `x' is position and `p' is momentum:

$$\Delta x \Delta p > \frac{h}{2\pi}$$

This is perhaps the most famous equation next to $E=mc^2$ in physics. It basically says that the combination of the error in position times the error in momentum must always be greater than Planck's constant. So, you can measure the position of an electron to some accuracy, but then its momentum will be inside a very large range of values. Likewise, you can measure the momentum precisely, but then its position is unknown.

Also notice that the uncertainty principle is unimportant to macroscopic objects since Planck's constant, h, is so small ($10^{-34}$). For example, the uncertainty in position of a thrown baseball is $10^{-30}$ millimeters.

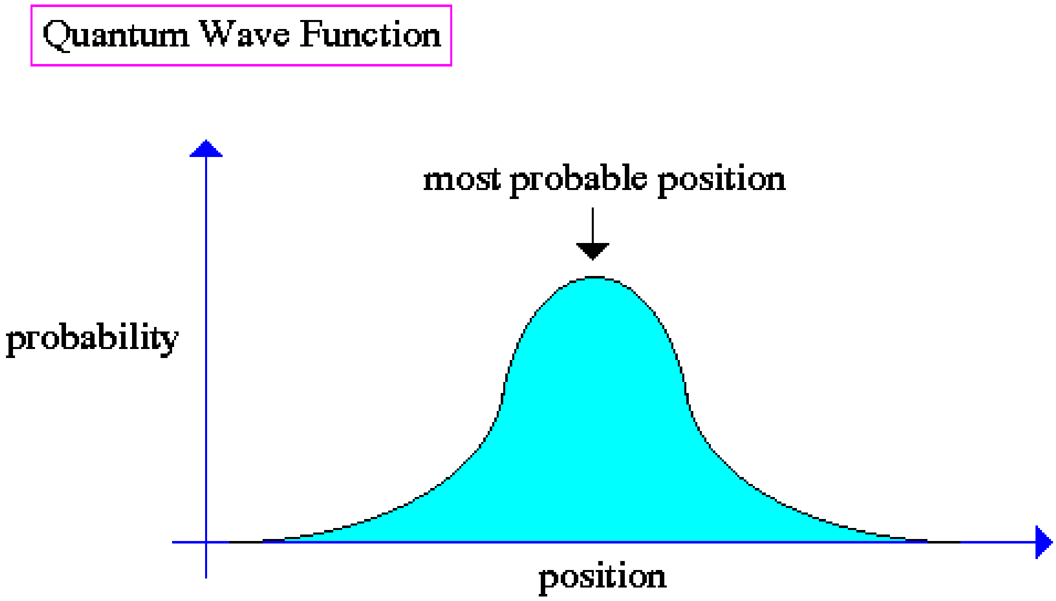
The depth of the uncertainty principle is realized when we ask the question; is our knowledge of reality unlimited? The answer is no, because the uncertainty principle states that there is a built-in uncertainty, indeterminacy, unpredictability to Nature.

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Quantum Wave Function:

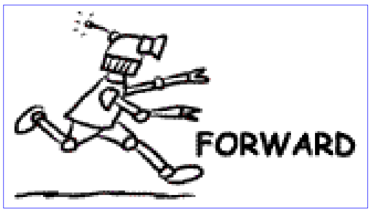
The wave nature of the microscopic world makes the concept of `position' difficult for subatomic particles. Even a wave packet has some `fuzziness' associated with it. An electron in orbit has no position to speak of, other than it is somewhere in its orbit.

To deal with this problem, quantum physics developed the tool of the quantum wave function as a mathematical description of the superpositions associated with a quantum entity at any particular moment.




The key point to the wave function is that the position of a particle is only expressed as a likelihood or probability *until* a measurement is made. For example, striking an electron with a photon results in a position measurement and we say that the wave function has `collapsed' (i.e. the wave nature of the electron converted to a particle nature).

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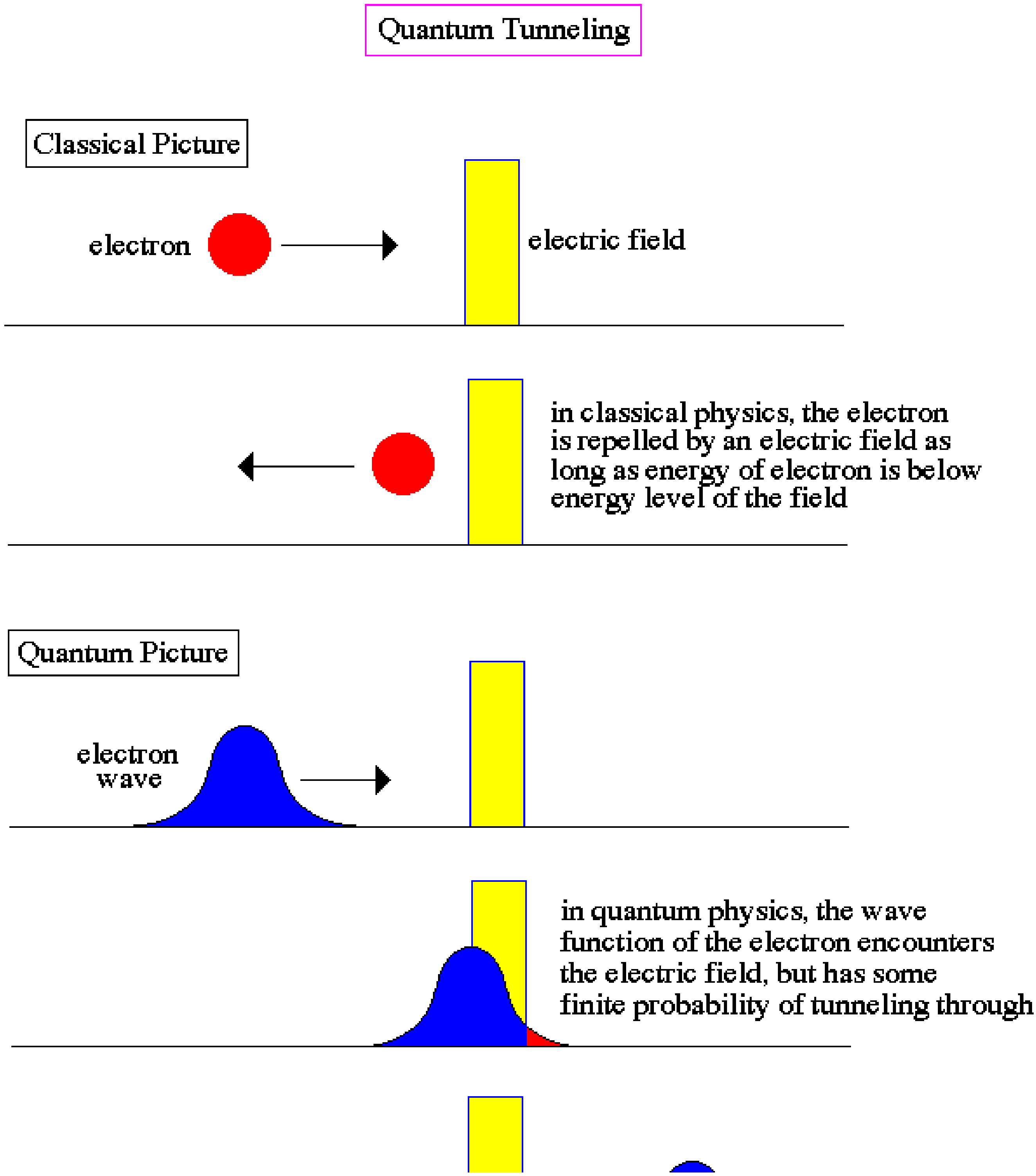


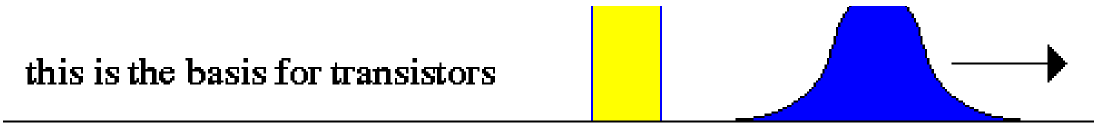



Superposition:

The fact that quantum systems, such as electrons and protons, have indeterminate aspects means they exist as possibilities rather than actualities. This gives them the property of being things that might be or might happen, rather than things that are. This is in sharp contrast to Newtonian physics where things are or are not, there is no uncertainty except those imposed by poor data or limitations of the data gathering equipment.

The superposition of possible positions for an electron can be demonstrated by the observed phenomenon called quantum tunneling.






Notice that the only explanation for quantum tunneling is if the position of the electron is truly spread out, not just hidden or unmeasured. It raw uncertainty allows for the wave function to penetrate the barrier. This is genuine indeterminism, not simply an unknown quantity until someone measures it.

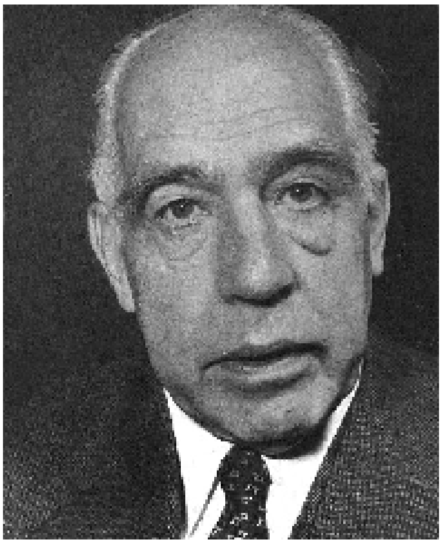
It is important to note that the superposition of possibilities only occurs before the entity is observed. Once an observation is made (a position is measured, a mass is determined, a velocity is detected) then the superposition converts to an actual. Or, in quantum language, we say the wave function has collapsed.

The collapse of the wave function by observation is a transition from the many to the one, from possibility to actuality. The identity and existence of a quantum entities are bound up with its overall environment (this is called contextualism). Like homonyms, words that depend on the context in which they are used, quantum reality shifts its nature according to its surroundings.

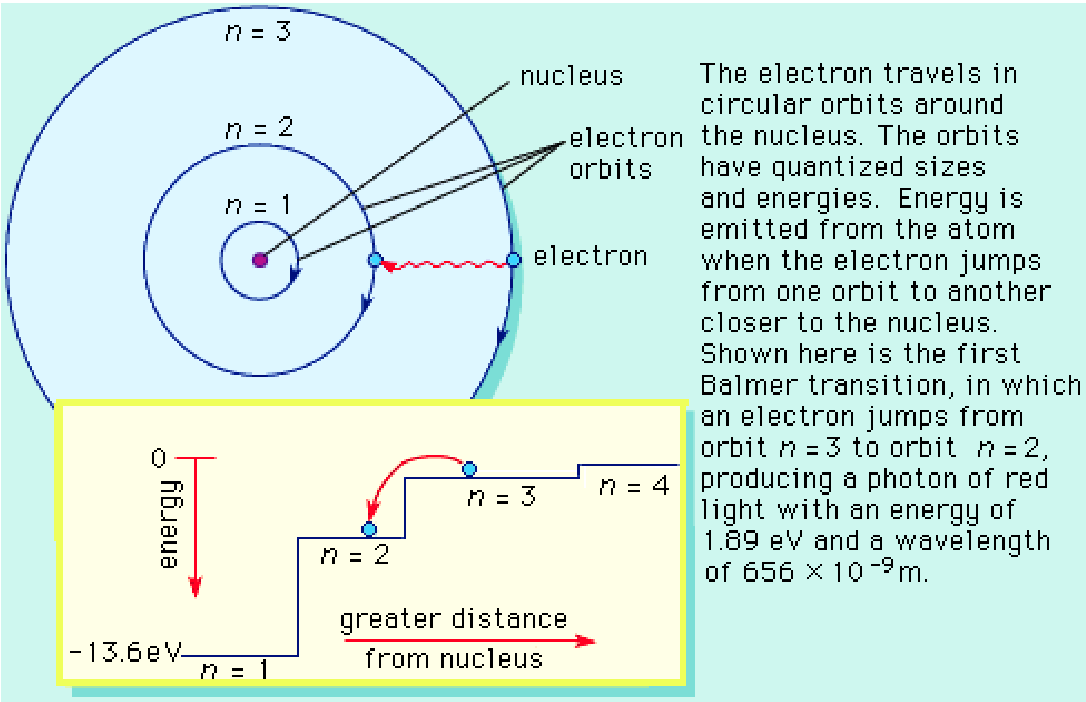
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Bohr Atom:

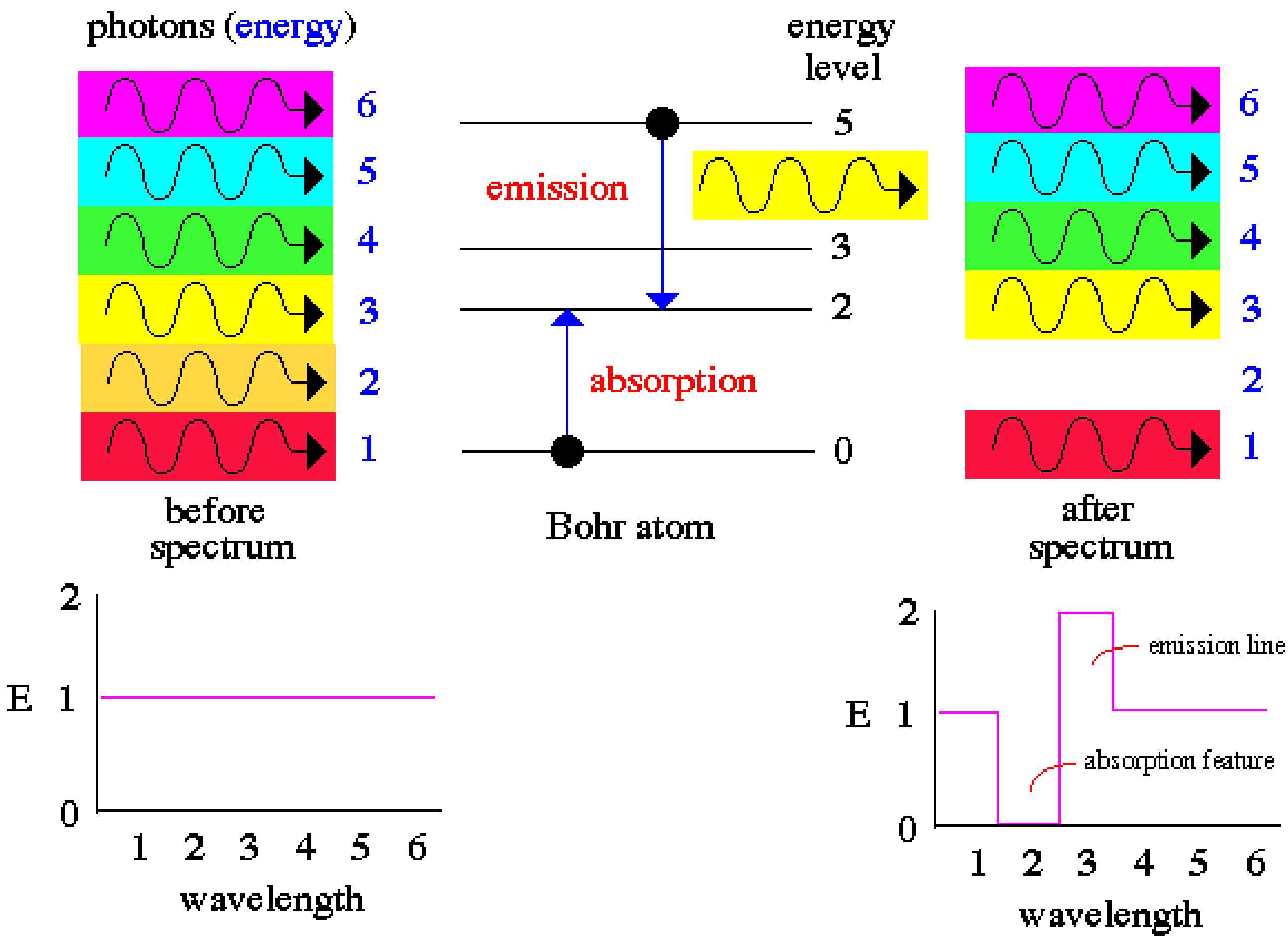
Perhaps the foremost scientists of the 20th century was Niels Bohr, the first to apply Planck's quantum idea to problems in atomic physics. In the early 1900's, Bohr proposed a quantum mechanical description of the atom to replace the early model of Rutherford.



The Bohr model basically assigned discrete orbits for the electron, multiples of Planck's constant, rather than allowing a continuum of energies as allowed by classical physics.




The power in the Bohr model was its ability to predict the spectra of light emitted by atoms. In particular, its ability to explain the spectral lines of atoms as the absorption and emission of photons by the electrons in quantized orbits.




In principle, all of atomic and molecular physics, including the structure of atoms and

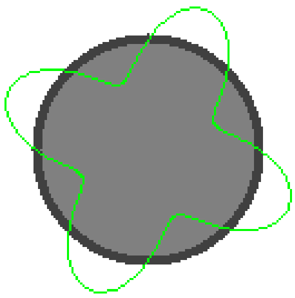
their dynamics, the periodic table of elements and their chemical behavior, as well as the spectroscopic, electrical, and other physical properties of atoms and molecules, can be accounted for by quantum mechanics => fundamental science.

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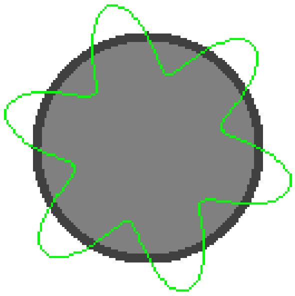
Quantum Mechanics:

The field of quantum mechanics concerns the description of phenomenon on small scales where classical physics breaks down. The biggest difference between the classical and microscopic realm, is that the quantum world can be not be perceived directly, but rather through the use of instruments. And a key assumption to quantum physics is that quantum mechanical principles must reduce to Newtonian principles at the macroscopic level (there is a continuity between quantum and Newtonian mechanics).

Quantum mechanics uses the philosophical problem of wave/particle duality to provide an elegant explanation to quantized orbits around the atom. Consider what a wave looks like around an orbit, as shown below.



n=4 orbit



n=6 orbit

Only certain wavelengths of an electron matter wave will `fit' into an orbit. If the wavelength is longer or shorter, then the ends do not connect. Thus, de Broglie matter waves explain the Bohr atom such that on certain orbits can exist to match the natural wavelength of the electron. If an electron is in some sense a wave, then in order to fit into an orbit around a nucleus, the size of the orbit must correspond to a whole number of wavelengths.

Notice also that this means the electron does not exist at one single spot in its orbit, it has a wave nature and exists at all places in the allowed orbit (the uncertainity

principle). Thus, a physicist speaks of allowed orbits and allowed transitions to produce particular photons (that make up the fingerprint pattern of spectral lines).

Quantum mechanics was capable of bringing order to the uncertainty of the microscopic world by treatment of the wave function with new mathematics. Key to this idea was the fact that relative probabilities of different possible states are still determined by laws. Thus, there is a difference between the role of chance in quantum mechanics and the unrestricted chaos of a lawless Universe.

The quantum description of reality is objective (weak form) in the sense that everyone armed with a quantum physics education can do the same experiments and come to the same conclusions. Strong objectivity, as in classical physics, requires that the picture of the world yielded by the sum total of all experimental results to be not just a picture or model, but identical with the objective world, something that exists outside of us and prior to any measurement we might have of it. Quantum physics does not have this characteristic due to its built-in indeterminacy.

For centuries, scientists have gotten used to the idea that something like strong objectivity is the foundation of knowledge. So much so that we have come to believe that it is an essential part of the scientific method and that without this most solid kind of objectivity science would be pointless and arbitrary. However, quantum physics denies that there is any such thing as a true and unambiguous reality at the bottom of everything. Reality is what you measure it to be, and no more. No matter how uncomfortable science is with this viewpoint, quantum physics is extremely accurate and is the foundation of modern physics (perhaps then an objective view of reality is not essential to the conduct of physics). And concepts, such as cause and effect, survive only as a consequence of the collective behavior of large quantum systems.

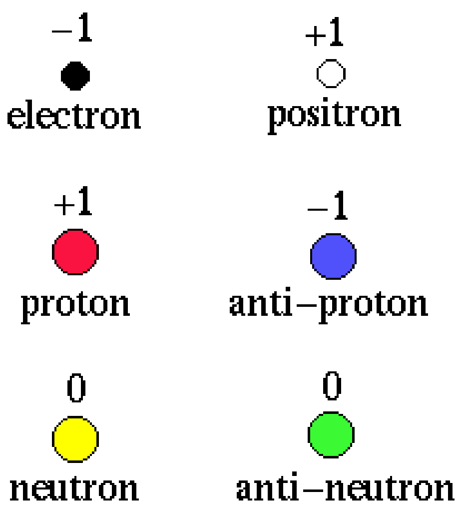
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Antimatter:

A combination of quantum mechanics and relativity allows us to examine subatomic processes in a new light. Symmetry is very important to physical theories. For example, conservation of momemtum is required for symmetry in time. Thus, the existence of a type of `opposite' matter was hypothesized soon after the development of quantum physics. `Opposite' matter is called antimatter. Particles of antimatter has the same mass and characteristics of regular matter, but opposite in charge. When matter and antimatter come in contact they are both instantaneously converted into pure energy, in the form of photons.

## Antimatter

All elementary particles have antimatter counterparts. Antimatter counterparts have the same mass, but opposite electric charge.




When matter and antimatter come in contact they are instantly converted into energy (annihilation).

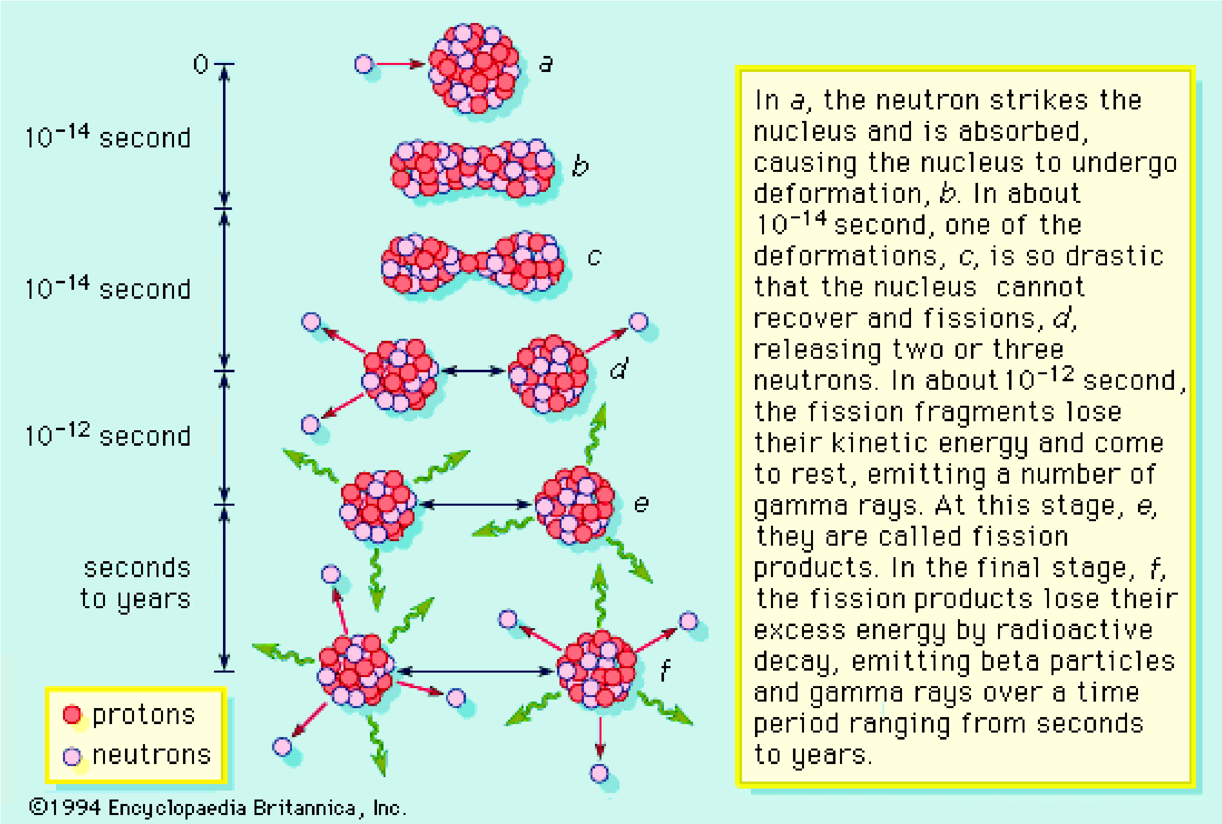
Antimatter is produced all the time by the collision of high energy photons, a process called pair production, where an electron and its antimatter twin (the positron) are created from energy ($E=mc^2$).

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Fission/Fusion:

One of the surprising results of quantum physics is that if a physical event is not specifically forbidden by a quantum rule, than it can and will happen. While this may strange, it is a direct result of the uncertainty principle. Things that are strict laws in the macroscopic world, such as the conversation of mass and energy, can be broken in the quantum world with the caveat that they can only broken for very small intervals of time (less than a Planck time). The violation of conservation laws led to the one of the greatest breakthroughs of the early 20th century, the understanding of radioactivity decay (fission) and the source of the power in stars (fusion).

Nuclear fission is the breakdown of large atomic nuclei into smaller elements. This can happen spontaneously (radioactive decay) or induced by the collision with a free neutron. Spontaneously fission is due to the fact that the wave function of a large nuclei is 'fuzzier' than the wave function of a small particle like the alpha particle. The uncertainty principle states that, sometimes, an alpha particle (2 protons and 2 neutrons) can tunnel outside the nucleus and escape.

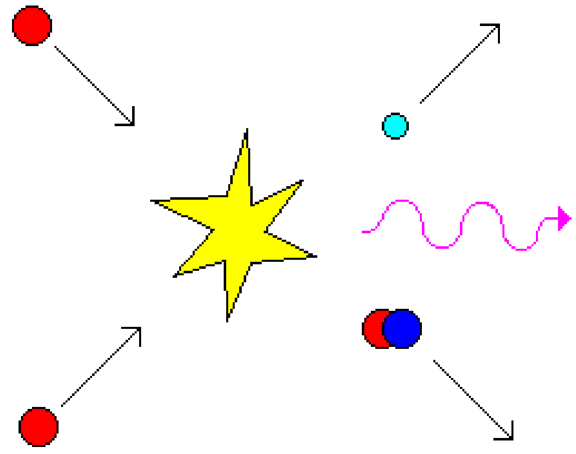



Induced fission occurs when a free neutron strikes a nucleus and deforms it. Under classical physics, the nucleus would just reform. However, under quantum physics there is a finite probability that the deformed nucleus will tunnel into two new nuclei and release some neutrons in the process, to produce a chain reaction.

Fusion is the production of heavier elements by the fusing of lighter elements. The process requires high temperatures in order to produce sufficiently high velocities for the two light elements to overcome each others electrostatic barriers.

Fusion

$$^{1}H_{1} + {}^{1}H_{1} \longrightarrow {}^{2}H_{1} + e^{+} + \nu$$



the 1st stage of the proton–proton chain is the fusion of two protons to produce deuterium, a positron and a neutrino – this is the energy source in the core of the Sun

Even for the high temperatures in the center of a star, fusion requires the quantum tunneling of a neutron or proton to overcome the repulsive electrostatic forces of an atomic nuclei. Notice that both fission and fusion release energy by converting some of the nuclear mass into gamma-rays, this is the famous formulation by Einstein that $E=mc^2$.

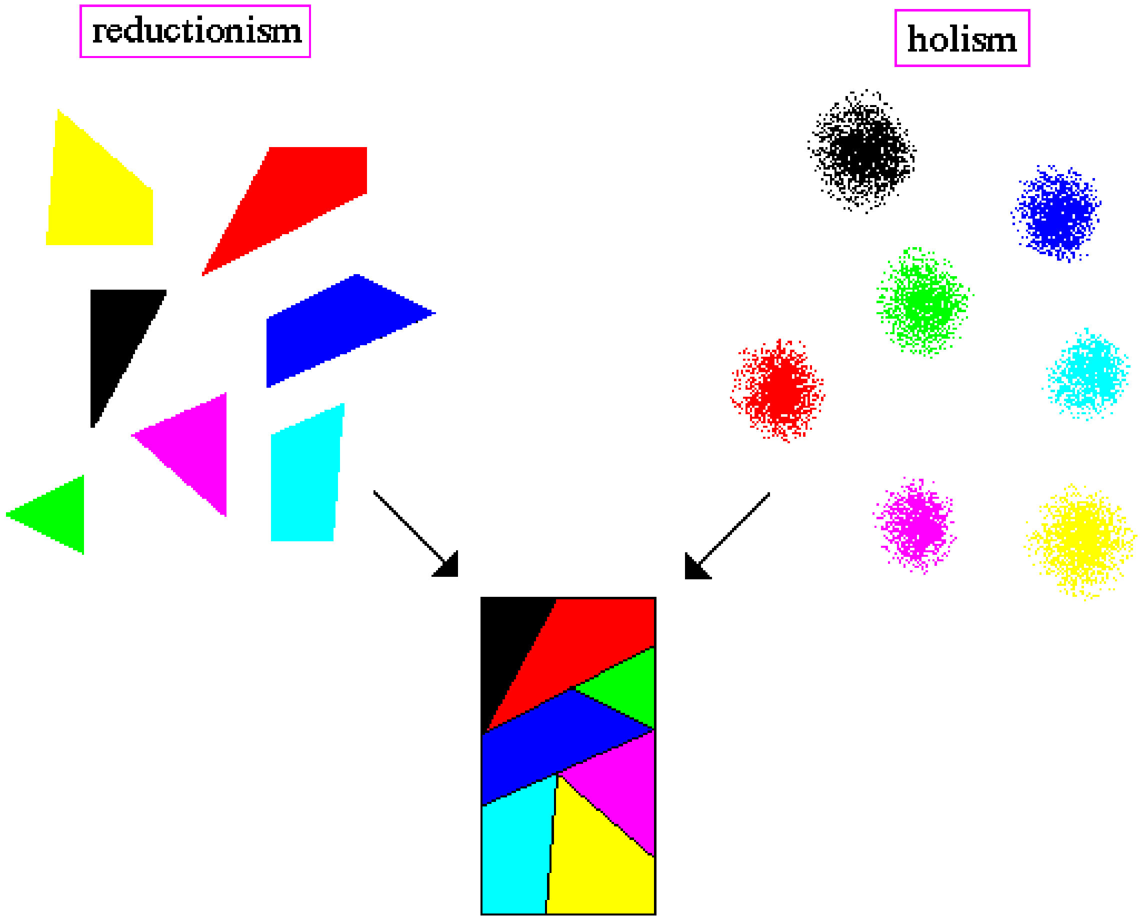
Although it deals with probabilities and uncertainties, the quantum mechanics has been spectacularly successful in explaining otherwise inaccessible atomic phenomena and in meeting every experimental test. Its predictions are the most precise and the best checked of any in physics; some of them have been tested and found accurate to better than one part per billion.

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Holism:

This is the holistic nature of the quantum world, with the behavior of individual particles being shaped into a pattern by something that cannot be explained in terms of the Newtonian reductionist paradigm. Newtonian physics is reductionistic, quantum physics is holistic.

Where a reductionist believes that any whole can be broken down or analyzed into its separate parts and the relationships between them, the holist maintains that the whole is primary and often greater than the sum of its parts. Nothing can be wholly reduced to the sum of its parts.

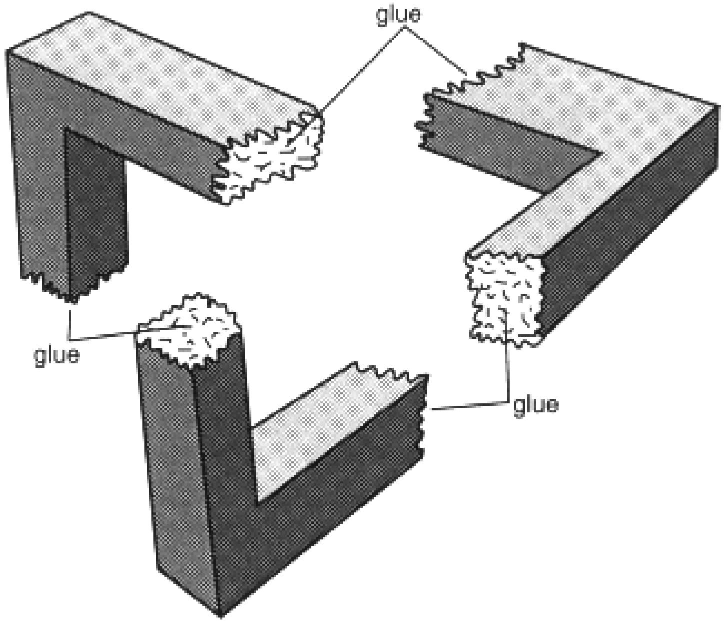



The atom theory of the Greeks viewed the Universe as consists of indestructible atoms. Change is a rearrangement of these atoms. An earlier holism of Parmenides argued that at some primary level the world is a changeless unity, indivisible and wholly continuous.

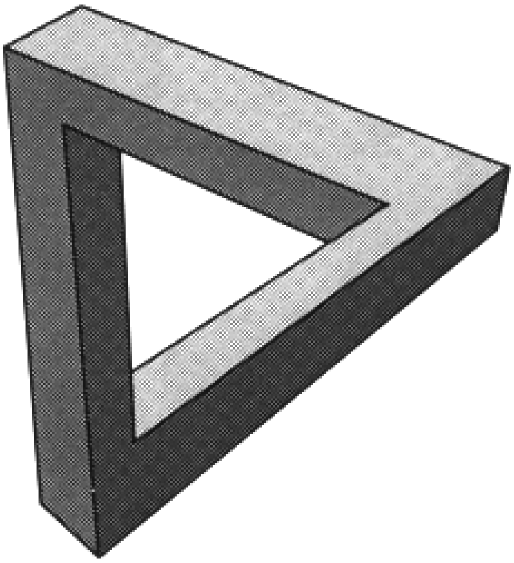
The highest development of quantum theory returns to the philosophy of Parmenides by describing all of existence as an excitation of the underlying quantum vacuum, like ripples on a universal pond. The substratum of all is the quantum vacuum, similar to Buddhist idea of permanent identity.

## Holism

as an example of the emergent property of holism consider the following three pieces of a triangle




and now consider what those pieces look like when assembled (if possible)



an impossible triangle

Quantum reality is a bizarre world of both/and, whereas macroscopic world is ruled by either/or. The most outstanding problem in modern physics is to explain how the both/and is converted to either/or during the act of observation.

Note that since there are most probable positions and energy associated with the wave function, then there is some reductionism available for the observer. The truth is somewhere between Newton and Parmenides.

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FORWARD

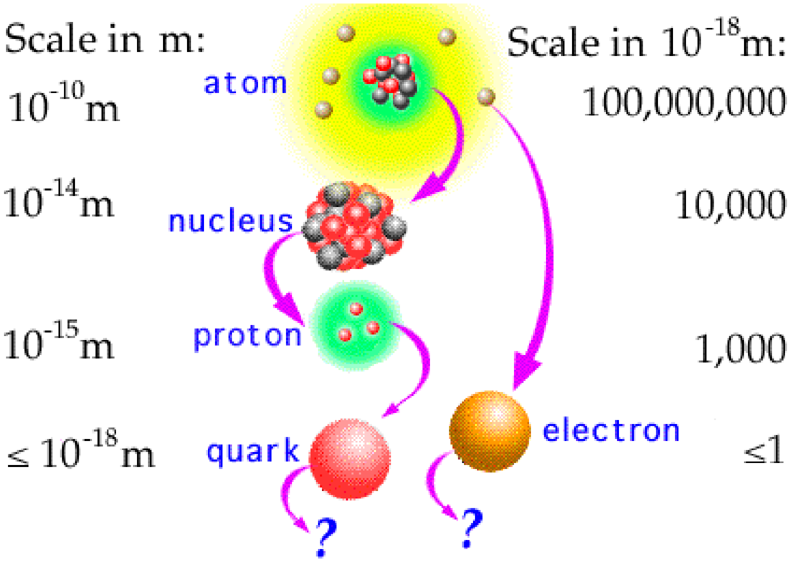

BACKWARD

Elementary Particles :

One of the primary goals in modern physics is to answer the question "What is the Universe made of?" Often that question reduces to "What is matter and what holds it together?" This continues the line of investigation started by Democritus, Dalton and Rutherford.

Modern physics speaks of fundamental building blocks of Nature, where fundamental takes on a reductionist meaning of simple and structureless. Many of the particles we have discussed so far appear simple in their properties. All electrons have the exact same characteristics (mass, charge, etc.), so we call an electron fundamental because they are all non-unique.

The search for the origin of matter means the understanding of elementary particles. And with the advent of holism, the understanding of elementary particles requires an understanding of not only their characteristics, but how they interact and relate to other particles and forces of Nature, the field of physics called particle physics.

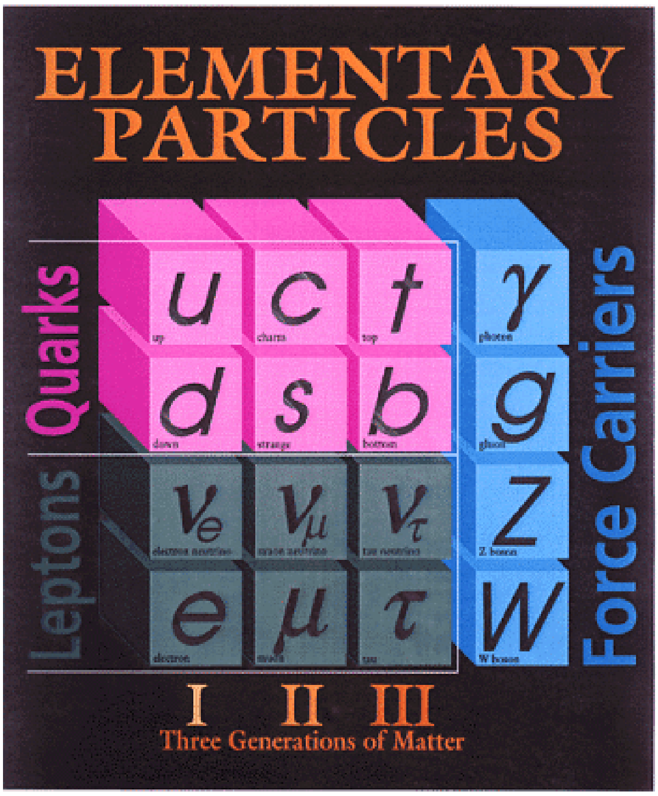



The study of particles is also a story of advanced technology begins with the search for the primary constituent. More than 200 subatomic particles have been discovered so far, all detected in sophisicated particle accerlators. However, most are not fundamental, most are composed of other, simplier particles. For example, Rutherford showed that the atom was composed of a nucleus and orbiting electrons. Later physicists showed that the nucleus was composed of neutrons and protons. More recent work has shown that protons and neutrons are composed of quarks.

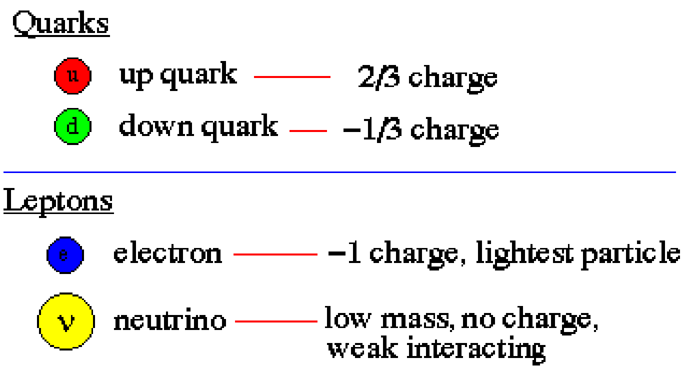
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Quarks and Leptons:

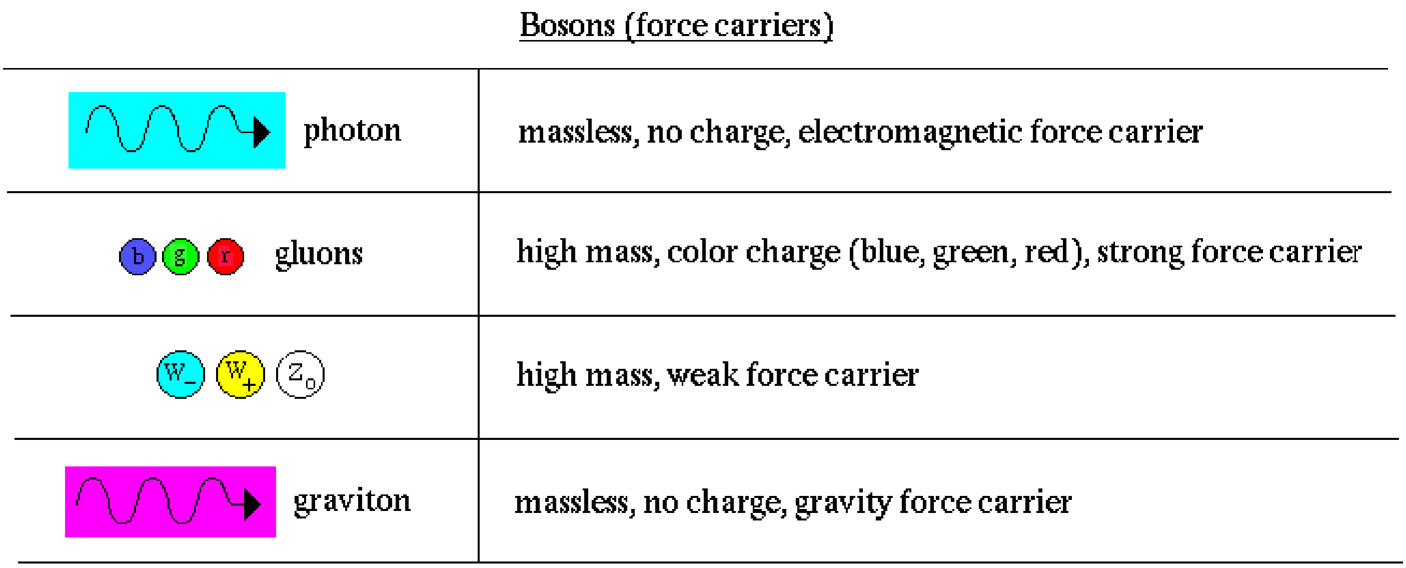
The two most fundamental types of particles are quarks and leptons. The quarks and leptons are divided into 6 flavors corresponding to three generations of matter. Quarks (and antiquarks) have electric charges in units of 1/3 or 2/3's. Leptons have charges in units of 1 or 0.




Normal, everyday matter is of the first generation, so we can concentrate our investigation to up and down quarks, the electron neutrino (often just called the neutrino) and electrons.




Note that for every quark or lepton there is a corresponding antiparticle. For example, there is an up antiquark, an anti-electron (called a positron) and an anti-neutrino. Bosons do not have antiparticles since they are force carriers (see fundamental forces).



Bosons (force carriers)

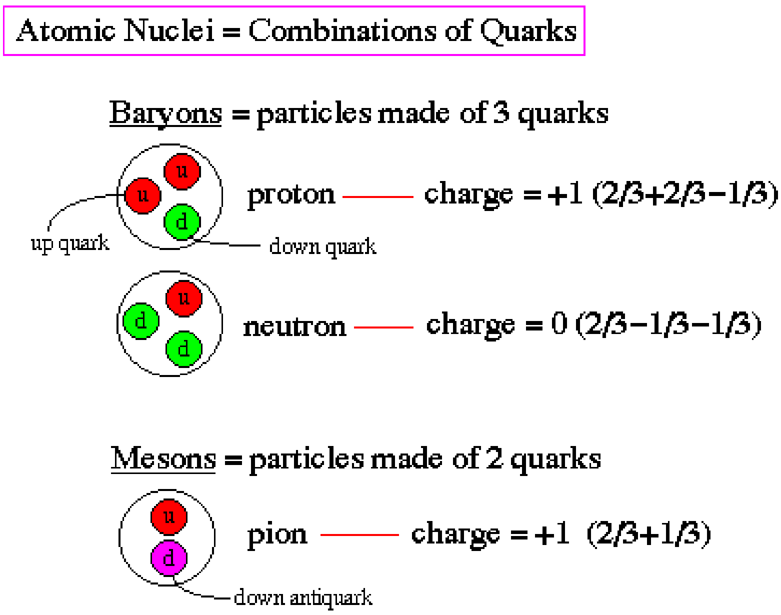
| | |
|---|---|
| photon | massless, no charge, electromagnetic force carrier |
| b g r gluons | high mass, color charge (blue, green, red), strong force carrier |
| $W_-$ $W_+$ $Z_0$ | high mass, weak force carrier |
| graviton | massless, no charge, gravity force carrier |

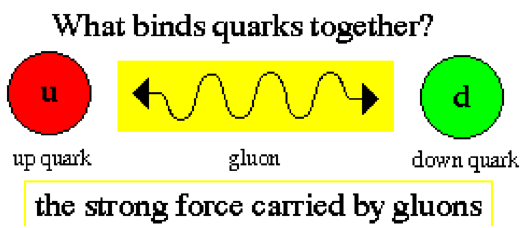
massless = moves at speed of light, long range
high mass = moves at less than speed of light, short range

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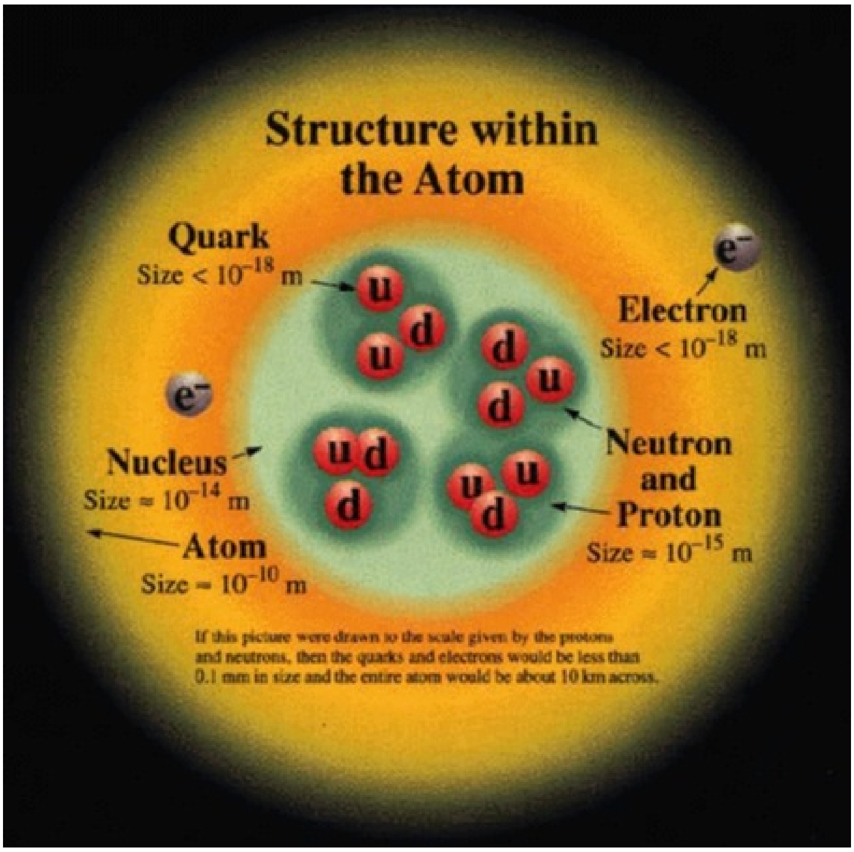
Baryons and Mesons:

Quarks combine to form the basic building blocks of matter, baryons and mesons. Baryons are made of three quarks to form the protons and neutrons of atomic nuclei (and also anti-protons and anti-neutrons). Mesons, made of quark pairs, are usually found in cosmic rays. Notice that the quarks all combine to make charges of -1, 0, or +1.



Thus, our current understanding of the structure of the atom is shown below, the atom contains a nucleus surrounded by a cloud of negatively charged electrons. The nucleus is composed of neutral neutrons and positively charged protons. The opposite charge of the electron and proton binds the atom together with electromagnetic forces.




The protons and neutrons are composed of up and down quarks whose fractional charges (2/3 and -1/3) combine to produce the 0 or +1 charge of the proton and neutron. The nucleus is bound together by the nuclear strong force (that overcomes the electronmagnetic repulsion of like-charged protons)

---

Color Charge:

Quarks in baryons and mesons are bound together by the strong force in the form of the exchange of gluons. Much like how the electromagnetic force strength is determined by the amount of electric charge, the strong force strength is determined by a new quantity called color charge.

Quarks come in three colors, red, blue and green (they are not actually colored, we just describe their color charge in these terms). So, unlike electromagnetic charges which come in two flavors (positive and negative or north and south poles), color charge in quarks comes in three types. And, just to be more confusing, color charge also has its anti-particle nature. So there is anti-red, anti-blue and anti-green.

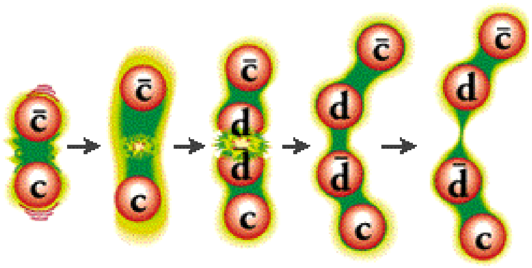
Gluons serve the function of carrying color when they interact with quarks. Baryons and mesons must have a mix of colors such that the result is white. For example, red, blue and green make white. Also red and anti-red make white.

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Quark Confinement:

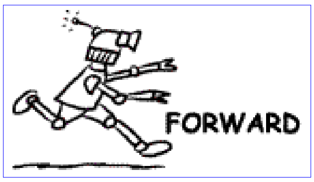
There can exist no free quarks, i.e. quarks by themselves. All quarks must be bound to another quark or antiquark by the exchange of gluons. This is called quark confinement. The exchange of gluons produces a color force field, referring to the assignment of color charge to quarks, similar to electric charge.

The color force field is unusual in that separating the quarks makes the force field stronger (unlike electromagnetic or gravity forces which weaken with distance). Energy is needed to overcome the color force field. That energy increases until a new quark or antiquark is formed (energy equals mass, $E=mc^2$).




Two new quarks form and bind to the old quarks to make two new mesons. Thus, none of the quarks were at anytime in isolation. Quarks always travel in pairs or triplets.

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Fundamental Forces :

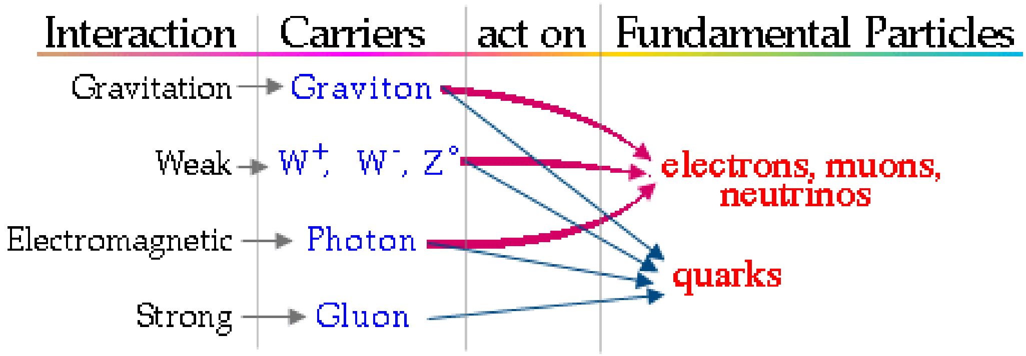
Matter is effected by forces or interactions (the terms are interchangeable). There are four fundamental forces in the Universe:

1. gravitation (between particles with mass)
2. electromagnetic (between particles with charge/magnetism)
3. strong nuclear force (between quarks)
4. weak nuclear force (operates between neutrinos and electrons)

The first two you are familiar with, gravity is the attractive force between all matter, electromagnetic force describes the interaction of charged particles and magnetics. Light (photons) is explained by the interaction of electric and magnetic fields.

The strong force binds quarks into protons, neutrons and mesons, and holds the nucleus of the atom together despite the repulsive electromagnetic force between protons. The weak force controls the radioactive decay of atomic nuclei and the reactions between leptons (electrons and neutrinos).

Current physics (called quantum field theory) explains the exchange of energy in interactions by the use of force carriers, called bosons. The long range forces have zero mass force carriers, the graviaton and the photon. These operate on scales larger than the solar system. Short range forces have very massive force carriers, the W+, W- and Z for the weak force, the gluon for the strong force. These operate on scales the size of atomic nuclei.




So, although the strong force has the greatest strength, it also has the shortest range.

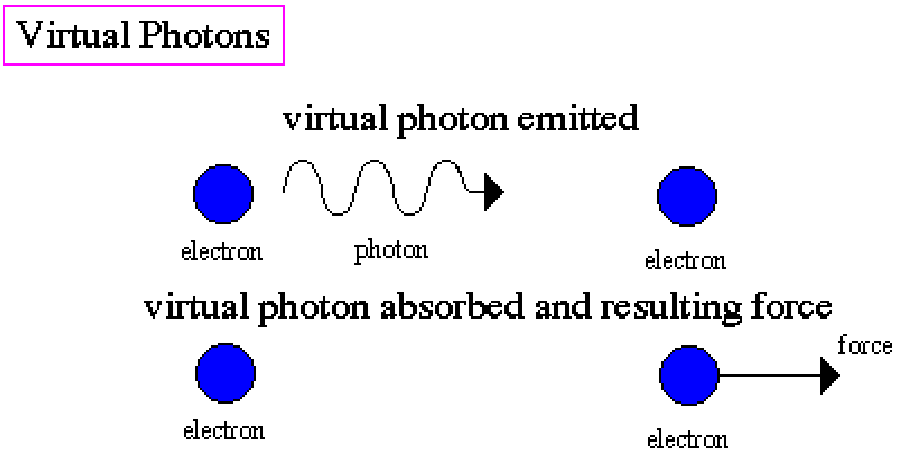
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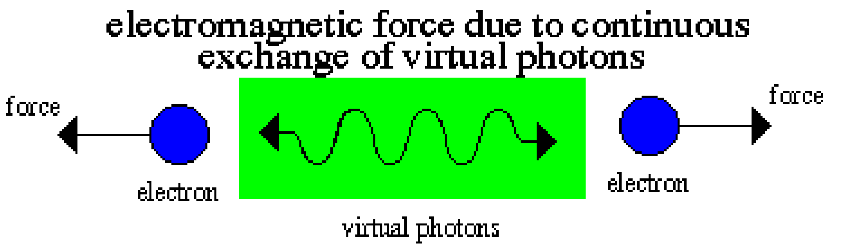
Quantum Electrodynamics :

The subfield of physics that explains the interaction of charged particles and light is called quantum electrodynamics. Quantum electrodynamics (QED) extends quantum theory to fields of force, starting with electromagnetic fields.

Under QED, charged particles interact by the exchange of virtual photons, photons that do not exist outside of the interaction and only serve as carriers of

momentum/force.




Notice the elimination of action at a distance, the interaction is due to direct contact of the photons.

In the 1960's, a formulation of QED led to the unification of the theories of weak and electromagnetic interactions. This new force, called electroweak, occurs at extremely high temperatures such as those found in the early Universe and reproduced in particle accerlators. Unification means that the weak and electromagnetic forces become symmetric at this point, they behave as if they were one force.

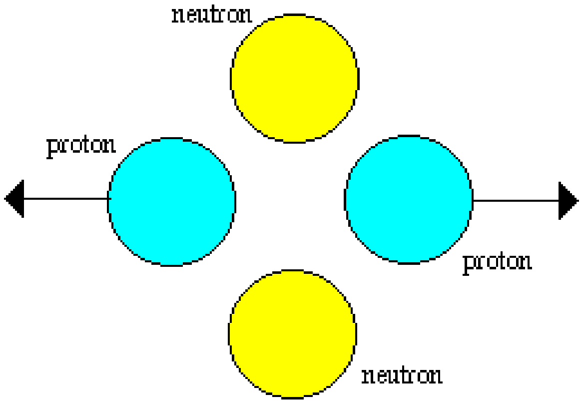
Electroweak unification gave rise to the belief that the weak, electromagnetic and strong forces can be unified into what is called the Standard Model of matter.

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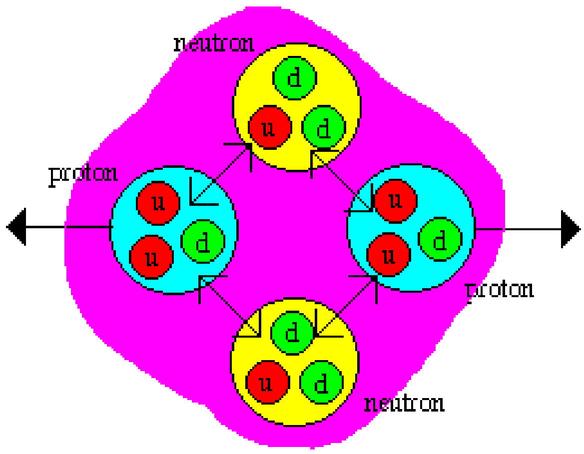
Quantum Chromodynamics:

Quantum chromodynamics is the subfield of physics that describes the strong or ``color'' force that binds quarks together to form baryons and mesons, and results in the complicated the force that binds atomic nuclei together.

## Color Force




an early dilemma for quantum mechanics was ''how does the nucleus of an atom hold together with the replusive electrostatic forces of the protons pulling it apart''




the answer is that the color force between quarks in the proton and neutron produce the strong force, which overcomes the electrostatic force

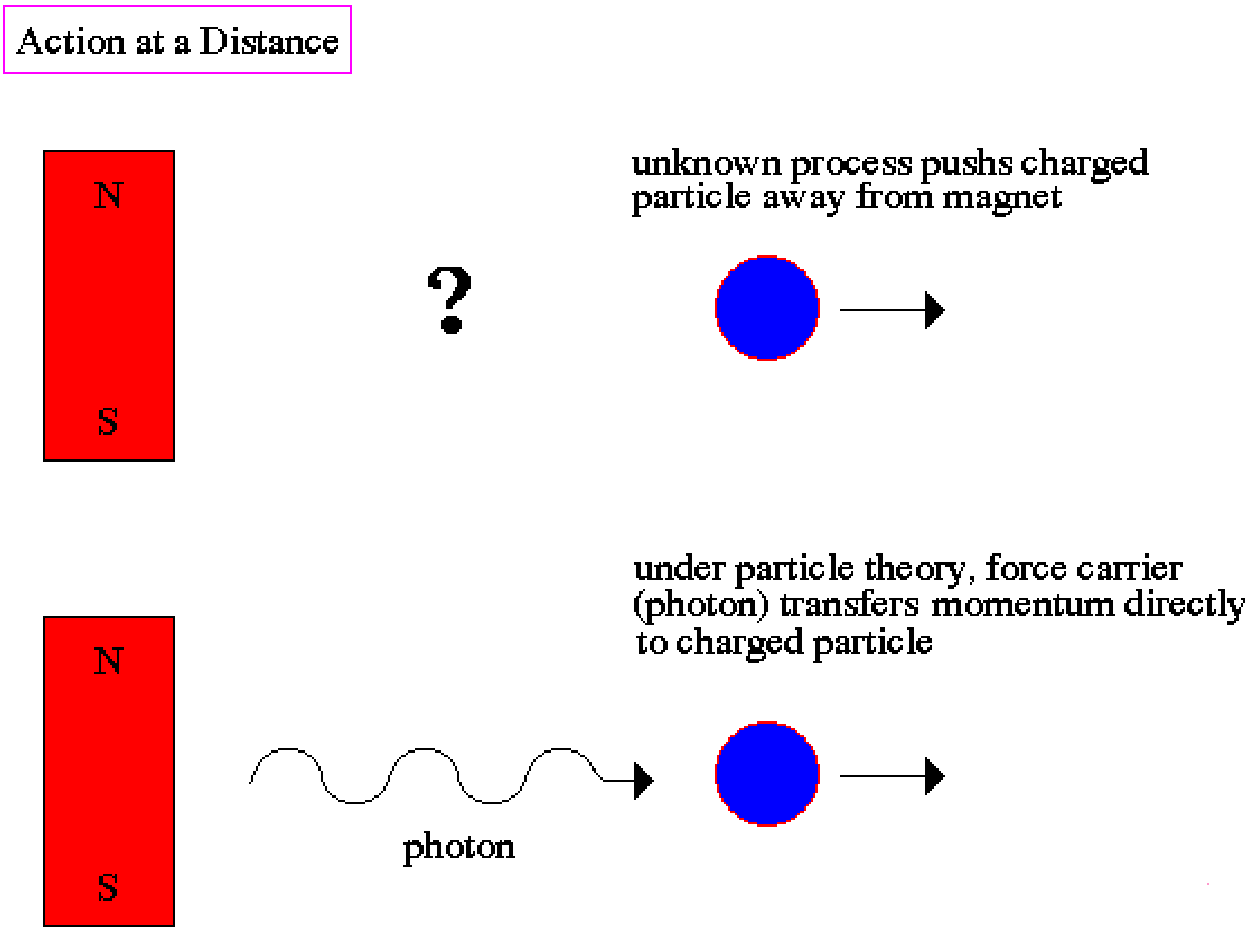
The strong force overcomes the electromagnetic or gravitational forces only on very short range. Outside the nucleus the effect of the strong force is non-existent.

---

Action at a Distance:

Newtonian physics assumes a direct connection between cause and effect. Electric and magnetic forces pose a dilemma for this interpretation since there is no direct contact between the two charges, rather there is an action at a distance.

To resolve this dilemma it was postulated that there is an exchange of force carriers between charged particles. These force carriers were later identified with particles of light (photons). These particles served to transfer momentum by contact between charged particles, much like colliding cars and trucks.




However, this attempt to resolve the action at a distance paradox uses a particle nature to light, when observation of interference patterns clearly shows that light has a wave-like nature. It was this dual nature to light, of both particle and wave (see wave/particle duality), that led to the revolution known as quantum physics.

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Theory of Everything:

Is that it? Are quarks and leptons the fundamental building blocks? Answer = maybe. We are still looking to fill some holes in what is know as the Standard Model.

The Standard Model is a way of making sense of the multiplicity of elementary particles and forces within a single scheme. The Standard Model is the combination of two schemes; the electroweak force (unification of electromagnetism and weak force) plus quantum chromodynamics. Although the Standard Model has brought a considerable amount of order to elementary particles and has led to important predictions, the model is not without some serious difficulties.

For example, the Standard Model contains a large number of arbitrary constants. Good choice of the constants leads to exact matches with experimental results. However, a good fundamental theory should be one where the constants are self-evident.

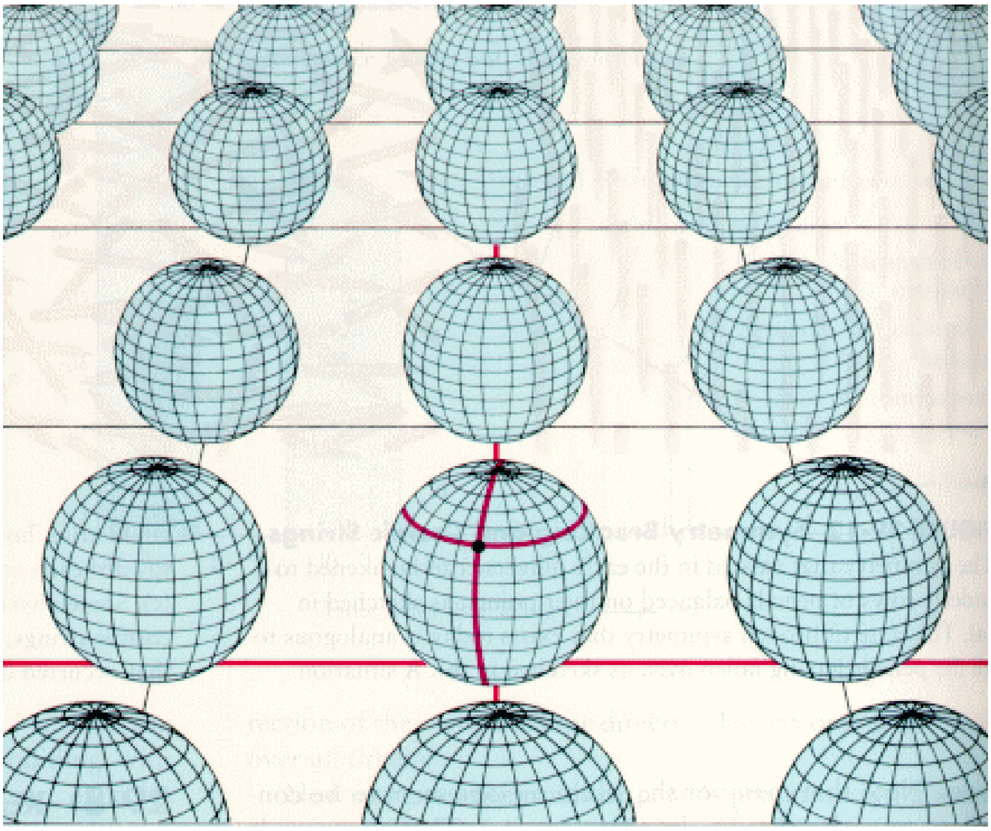
The Standard Model does not include the unification of all forces and, therefore, is incomplete. There is a strong expectation that there exists a Grand Unified Field Theory (GUTS) that will provide a deeper meaning to the Standard Model and explain the missing elements.

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Supergravity:

Even a GUTS is incomplete because it would not include spacetime and therefore gravity. It is hypothesized that a ``Theory of Everything'' (TOE) will bring together all the fundamental forces, matter and curved spacetime under one unifying picture. For cosmology, this will be the single force that controlled the Universe at the time of formation. The current approach to the search for a TOE is to attempt to uncover some fundamental symmetry, perhaps a symmetry of symmetries. There should be predictions from a TOE, such as the existence of the Higgs particle, the origin of mass in the Universe.

One example of a attempt to formula a TOE is supergravity, a quantum theory that unities particle types through the use of ten dimensional spacetime (see diagram below). Spacetime (4D construct) was successful at explaining gravity. What if the subatomic world is also a geometric phenomenon.



Many more dimensions of time and space could lie buried at the quantum level, outside our normal experience, only having an impact on the microscopic world of elementary particles.

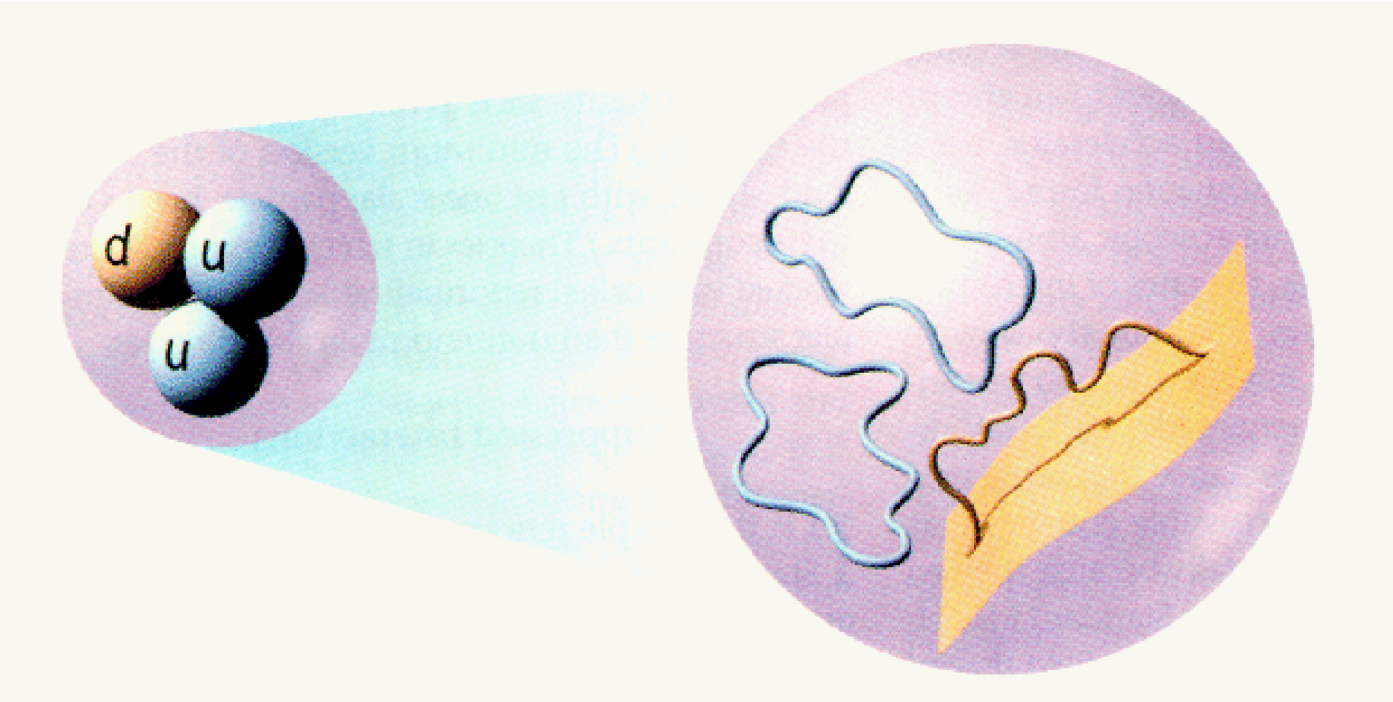
It is entirely possible that beneath the quantum domain is a world of pure chaos,

without any fixed laws or symmetries. One thing is obvious, that the more our efforts reach into the realm of fundamental laws, the more removed from experience are the results.

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String Theory:

Another recent attempt to form a TOE is through M (for membrane) or string theory. String theory is actually a high order theory where other models, such as supergravity and quantum gravity, appear as approximations. The basic premise to string theory is that subatomic entities, such as quarks and forces, are actually tiny loops, strings and membranes that behave as particles at high energies.



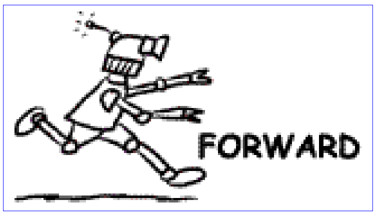

One of the problems in particle physics is the bewildering number of elementary particles (muons and pions and mesons etc). String theory answers this problem by proposing that small loops, about 100 billion billion times smaller than the proton, are vibrating below the subatomic level and each mode of vibration represents a distinct resonance which corresponds to a particular particle. Thus, if we could magnify a quantum particle we would see a tiny vibrating string or loop.

The fantastic aspect to string theory, that makes it such an attractive candidate for a TOE, is that it not only explains the nature of quantum particles but it also explains spacetime as well. Strings can break into smaller strings or combine to form larger strings. This complicated set of motions must obey self-consistent rules and the the constraint caused by these rules results in the same relations described by relativity theory.

Another aspect of string theory that differs from other TOE candidates is its high aesthetic beauty. For string theory is a geometric theory, one that, like general relativity, describes objects and interactions through the use of geometry and does not

suffer from infinites or what is called normalization problems such as quantum mechanics. It may be impossible to test the predictions of string theory since it would require temperature and energies similar to those at the beginning of the Universe. Thus, we resort to judging the merit of this theory on its elegance and internal consistence rather than experiment data.

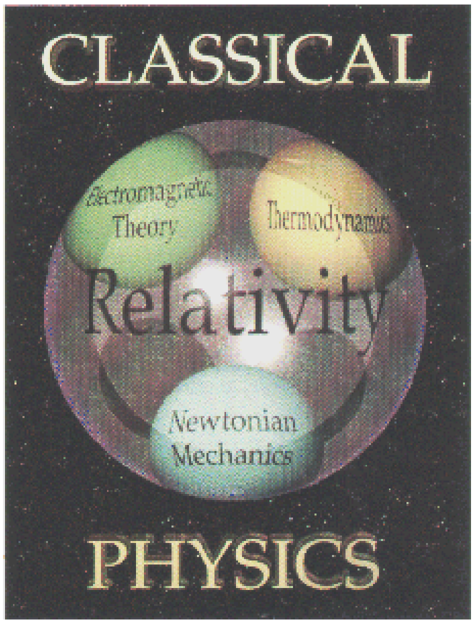
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Relativity:

Einstein's theory of relativity deals with Newtonian physics when energies or velocities are near the speed of light. Relativity is usually thought of as modern physics since it was developed at the start of the 20th century and could only be tested in the realm available to scientists by high technology. However, relativity primarily completes the revolution that Newton started and is also highly deterministic as is much of classical physics.




In the holistic viewpoint of relativity theory, concepts such as length, mass and time take on a much more nebulous aspect than they do in the apparently rigid reality of our everyday world. However, what relativity takes away with one hand, it gives back in the form of new and truly fundamental constants and concepts.

The theory of relativity is traditionally broken into two parts, special and general relativity. Special relativity provides a framework for translating physical events and laws into forms appropriate for any inertial frame of reference. General relativity addresses the problem of accelerated motion and gravity.

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Special Theory of Relativity:

By the late 1800's, it was becoming obvious that there were some serious problems for Newtonian physics concerning the need for absolute space and time when referring to events or interactions (frames of reference). In particular, the newly formulated theory of electromagnetic waves required that light propagation occur in a medium (the waves had to be waves on something).

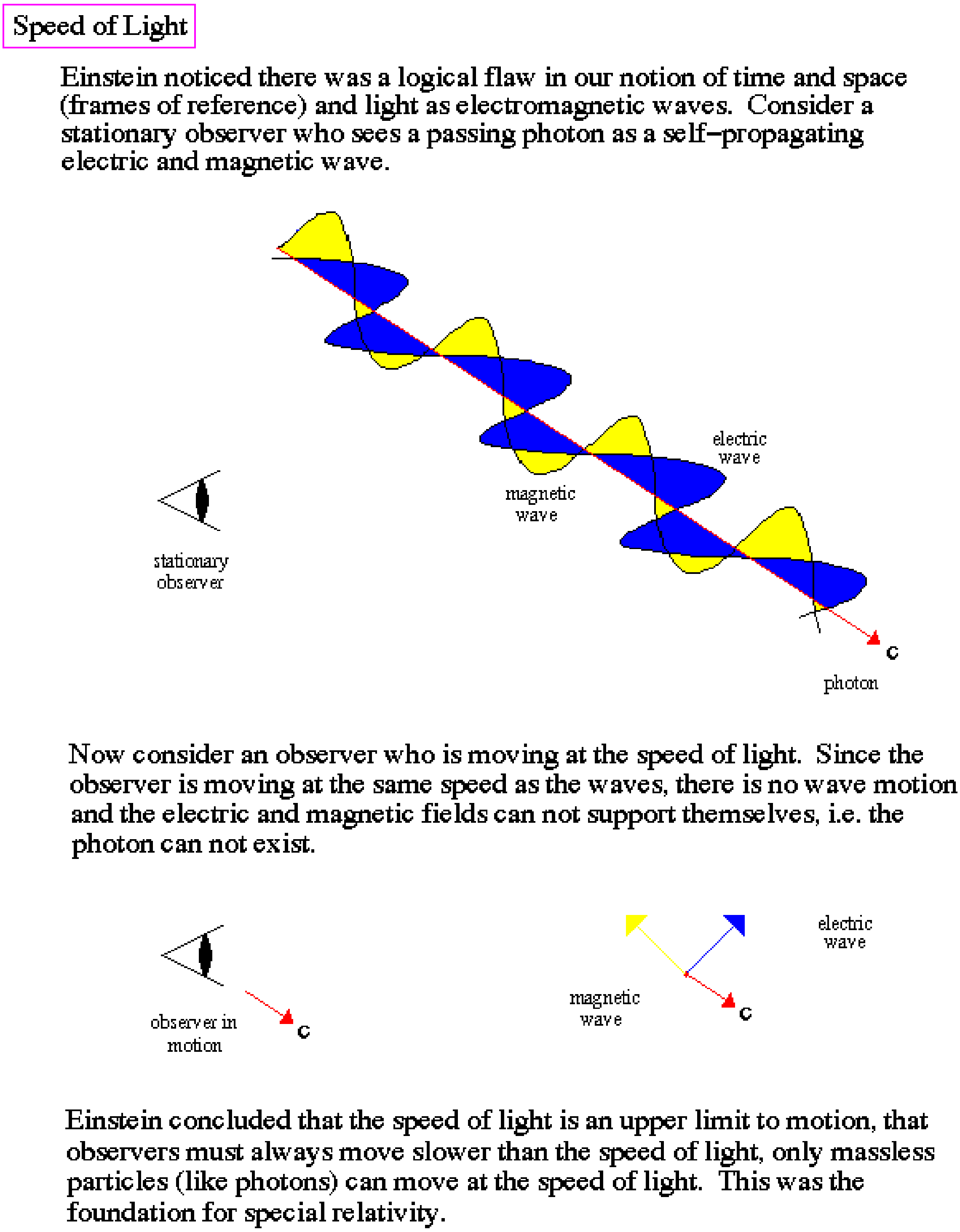
In a Newtonian Universe, there should be no difference in space or time regardless of where you are or how fast you are moving. In all places, a meter is a meter and a second is a second. And you should be able to travel as fast as you want, with enough acceleration (i.e. force).

In the 1890's, two physicists (Michelson and Morley) were attempting to measure the Earth's velocity around the Sun with respect to Newtonian Absolute space and time. This would also test how light waves propagated since all waves must move through a medium. For light, this hypothetical medium was called the aether.

The results of the Michelson-Morley experiment was that the velocity of light was constant regardless of how the experiment was tilted with respect to the Earth's motion. This implied that

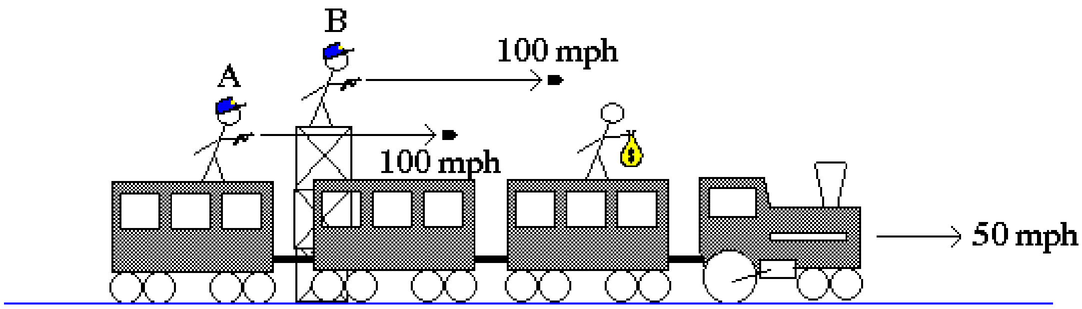
there was no aether and, thus, no absolute space. Thus, objects, or coordinate systems, moving with constant velocity (called inertial frames) were relative only to themselves.

In Newtonian mechanics, quantities such as speed and distance may be transformed from one frame of reference to another, provided that the frames are in uniform motion (i.e. not accelerating).

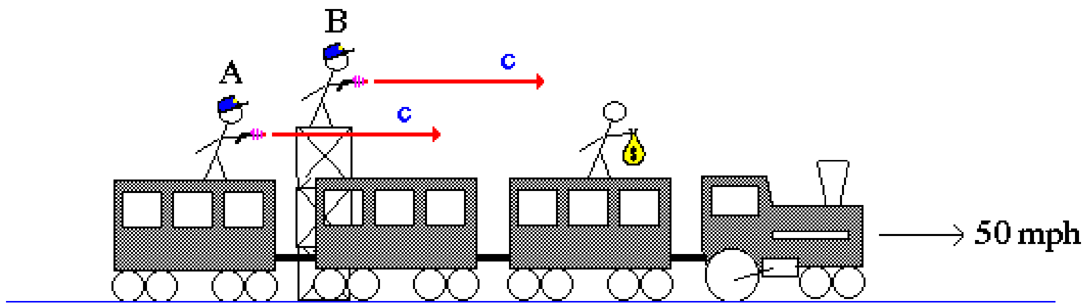



Considering the results of the Michelson-Morley experiment led Einstein to develop the theory of special relativity. The key premise to special relativity is that the speed of light (called *c* = 186,000 miles per sec) is constant in all frames of reference, regardless of their motion. What this means can be best demonstrated by the following scenario:

Relativistic Train Robbery




bullet from A strikes train robber at 100 mph (due to inertia), bullet from B strikes train robber at 100−50 = 50 mph

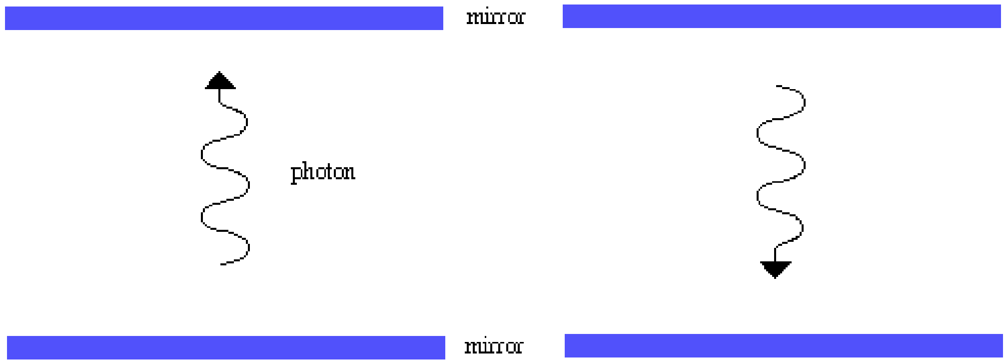



relativity states that the speed of light is constant in all frames, thus the light rays from both A and B strike the train robber at the same time, and at the speed of light, c.

This eliminates the paradox with respect to Newtonian physics and electromagnetism of what does a light ray `look like' when the observer is moving at the speed of light. The solution is that only massless photons can move at the speed of light, and that matter must remain below the speed of light regardless of how much acceleration is applied.

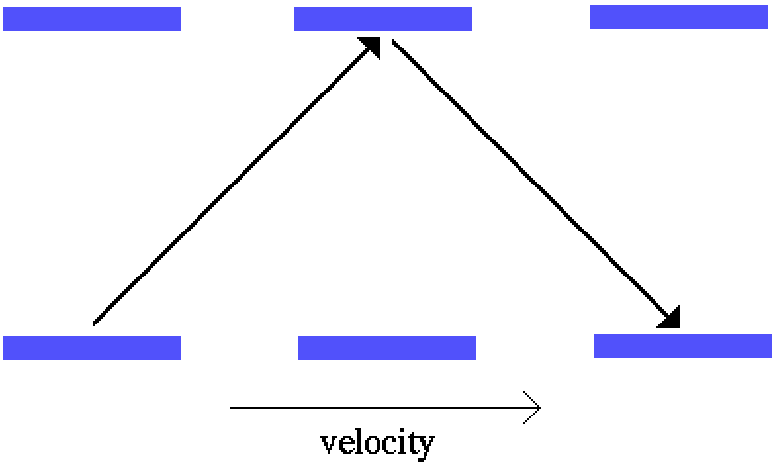
In special relativity, there is a natural upper limit to velocity, the speed of light. And the speed of light the same in all directions with respect to any frame. A surprising result to the speed of light limit is that clocks can run at different rates, simply when they are traveling a different velocities.

## Photon Clock



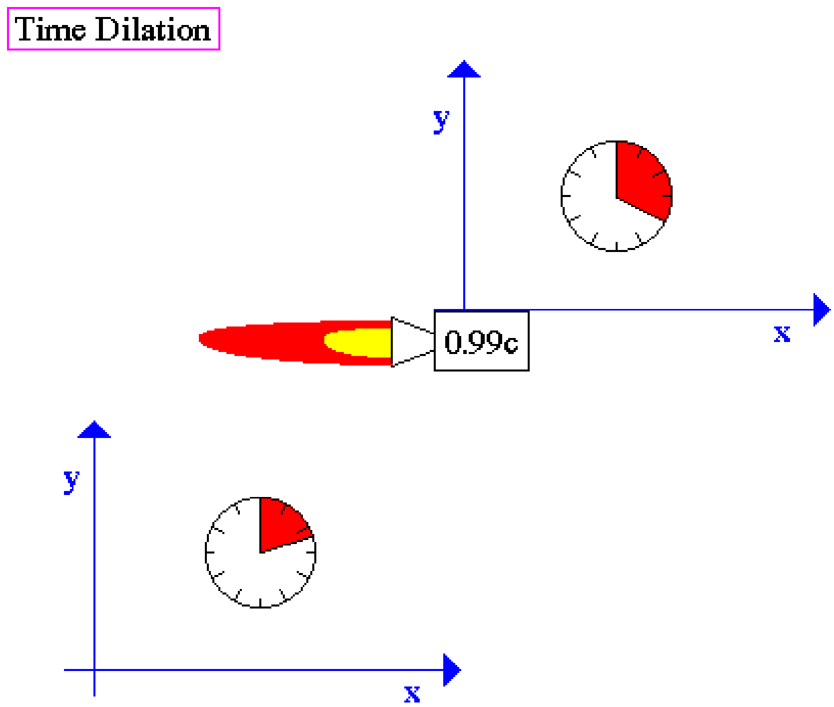

A photon clock is a device that consists of two mirrors and a photon passing between them. Each time the photon strikes a mirror corresponds to one 'tick' of the clock.

To understand time dilation, consider a moving photon clock. Since special relativity says that a photon must travel at a constant speed (c), then the path of the photon for a moving clock is longer than a clock at rest.



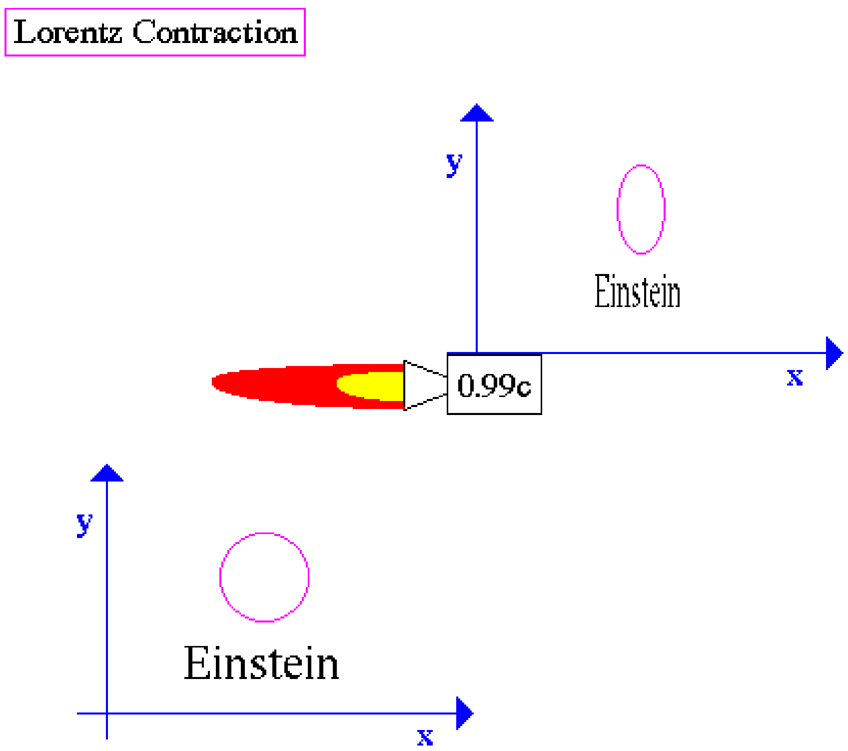

Therefore, the time between 'ticks' is longer for a moving clock, as seen from a rest frame.

This means that time (and space) vary for frames of reference moving at different velocities with respect to each other. The change in time is called time dilation, where frames moving near the speed of light have slow clocks.




clocks run slower as one approaches the speed of light

Likewise, space is shorten in in high velocity frames, which is called Lorentz contraction.

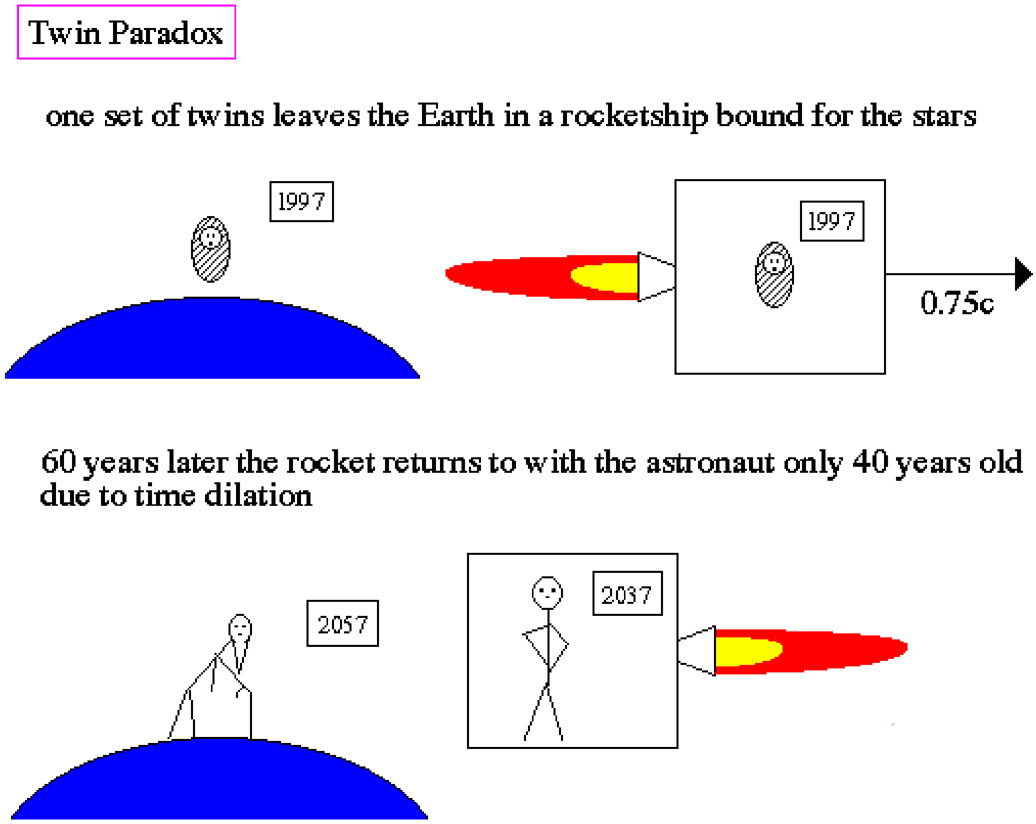



an object moving close to the speed of light appears shortened

Space-Time Lab

Time dilation leads to the famous Twins Paradox, which is not a paradox but rather a simple fact of special relativity. Since clocks run slower in frames of reference at high velocity, then one can imagine a scenario were twins age at different rates when separated at birth due to a

trip to the stars.




It is important to note that all the predictions of special relativity, length contraction, time dilation and the twin paradox, have been confirmed by direct experiments, mostly using sub-atomic particles in high energy accelerators. The effects of relativity are dramatic, but only when speeds approach the speed of light. At normal velocities, the changes to clocks and rulers are too small to be measured.

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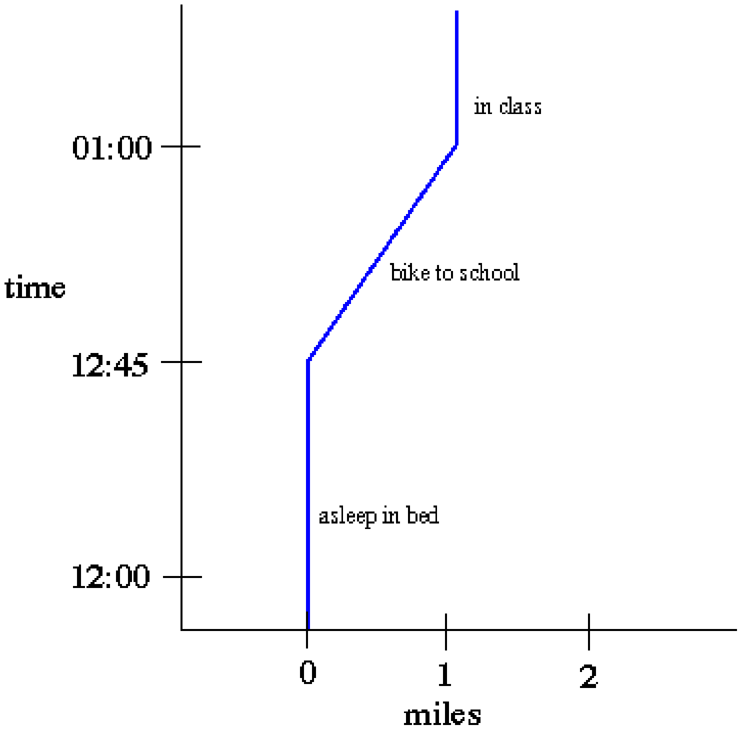
Spacetime:

Special relativity demonstrated that there is a relationship between spatial coordinates and temporal coordinates. That we can no longer reference where without some reference to when. Although time remains physically distinct from space, time and the three dimensional space coordinates are so intimately bound together in their properties that it only makes sense to describe them jointly as a four dimensional continuum.

Einstein introduced a new concept, that there is an inherent connection between geometry of the Universe and its temporal properties. The result is a four dimensional (three of space, one of time) continuum called spacetime which can best be demonstrated through the use of Minkowski diagrams and world lines.

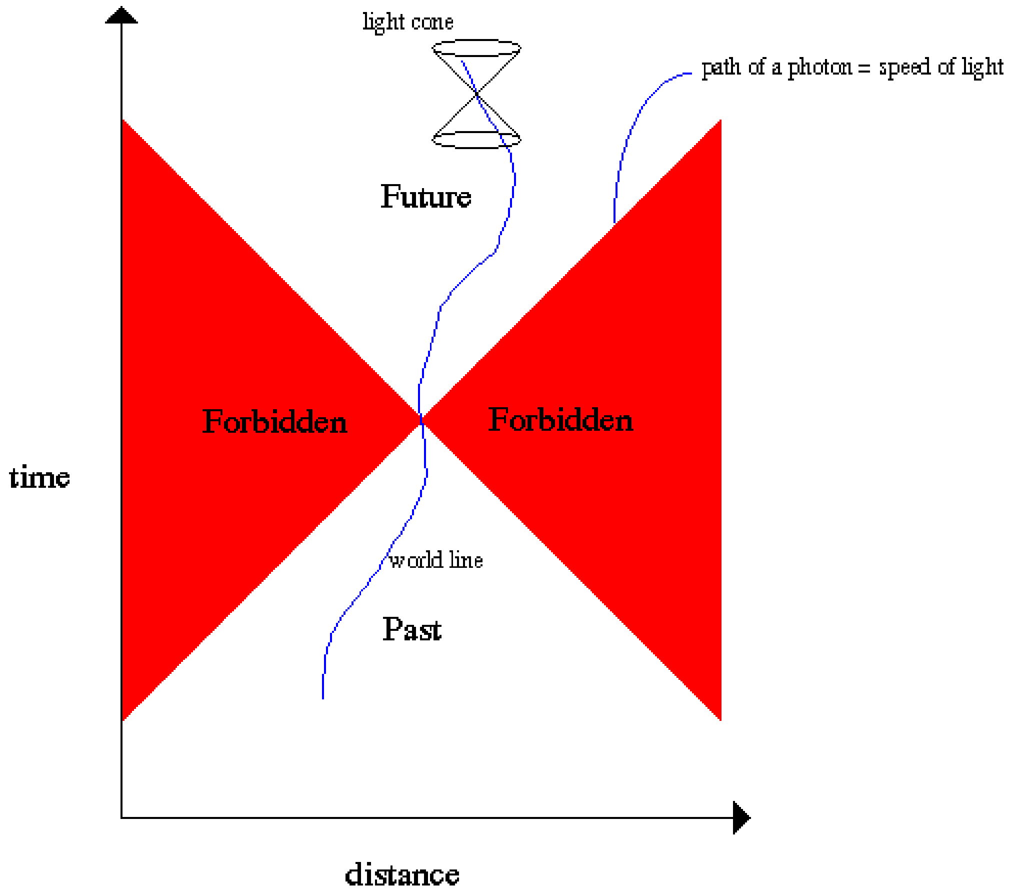
## World Lines

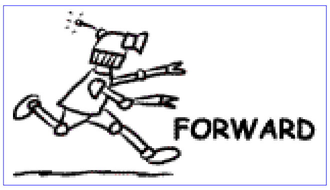
A world line is the plot of an event or object in spacetime. Typically only one of the 3 spatial coordinates are shown in order to make a flat plot




Spacetime makes sense from special relativity since it was shown that spatial coordinates (Lorentz contraction) and temporal coordinates (time dilation) vary between frames of reference. Notice that under spacetime, time does not `happen' as perceived by humans, but rather all time exists, stretched out like space in its entirety. Time is simply `there'.

## Light Cones


light cone
path of a photon = speed of light
Future
Forbidden
Forbidden
time
world line
Past
distance


FORWARD


BACKWARD

Mass-Energy Equivalence:

Since special relativity demonstrates that space and time are variable concepts from different frames of reference, then velocity (which is space divided by time) becomes a variable as well. If velocity changes from reference frame to reference frame, then concepts that involve velocity must also be relative. One such concept is momentum, motion energy.

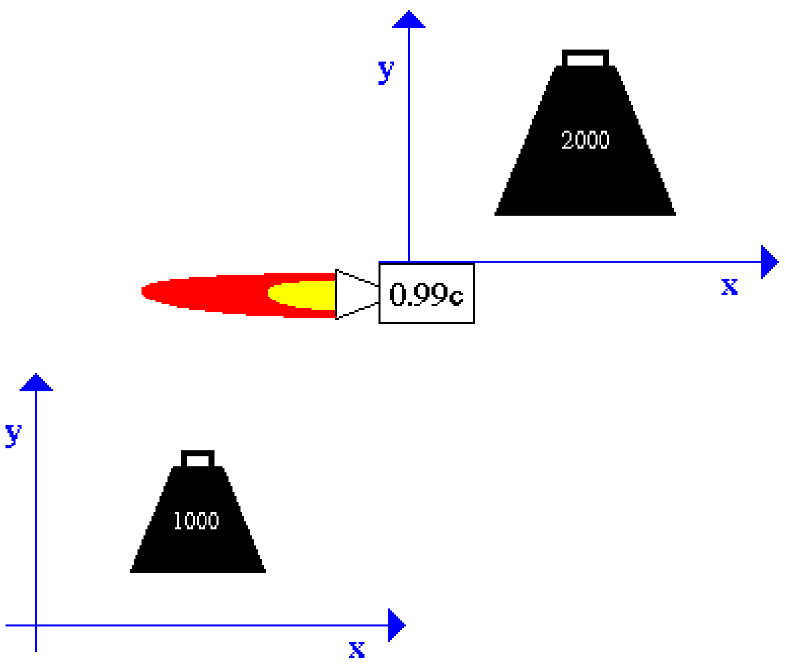
Momentum, as defined by Newtonian, can not be conserved from frame to frame under special relativity. A new parameter had to be defined, called relativistic momentum, which is conserved, but only if the mass of the object is added to the momentum equation.

This has a big impact on classical physics because it means there is an equivalence between mass and energy, summarized by the famous Einstein equation:

$$E = mc^2$$

The implications of this was not realized for many years. For example, the production of energy in nuclear reactions (i.e. fission and fusion) was shown to be the conversion of a small amount of atomic mass into energy. This led to the development of nuclear power and weapons.

As an object is accelerated close to the speed of light, relativistic effects begin to dominate. In particular, adding more energy to an object will not make it go faster since the speed of light is the limit. The energy has to go somewhere, so it is added to the mass of the object, as observed from the rest frame. Thus, we say that the observed mass of the object goes up with increased velocity. So a spaceship would appear to gain the mass of a city, then a planet, than a star, as its velocity increased.

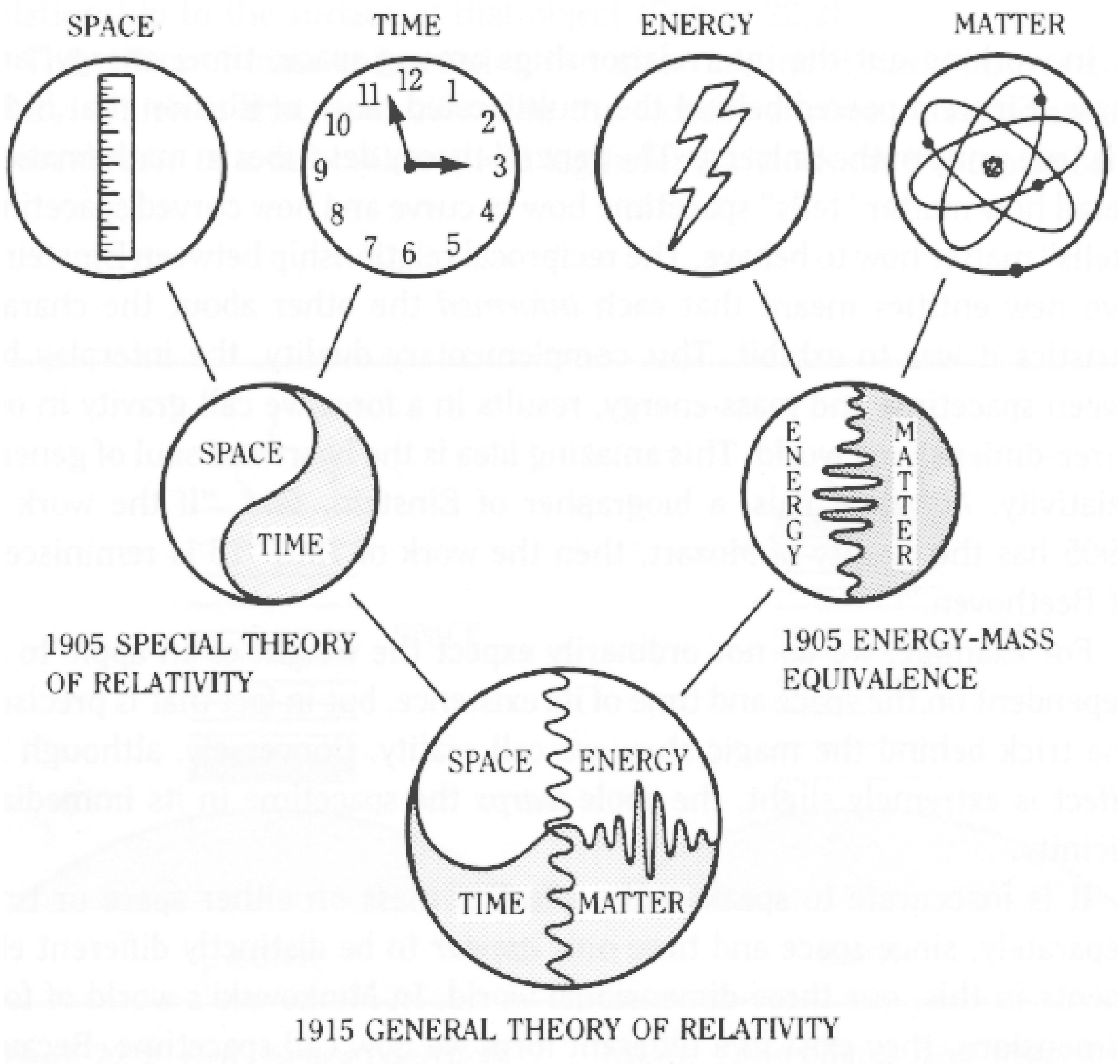



an objects mass increases as it approaches the speed of light

Likewise, the equivalence of mass and energy allowed Einstein to predict that the photon has momentum, even though its mass is zero. This allows the development of light sails and photoelectric detectors.

Spacetime and Energy:

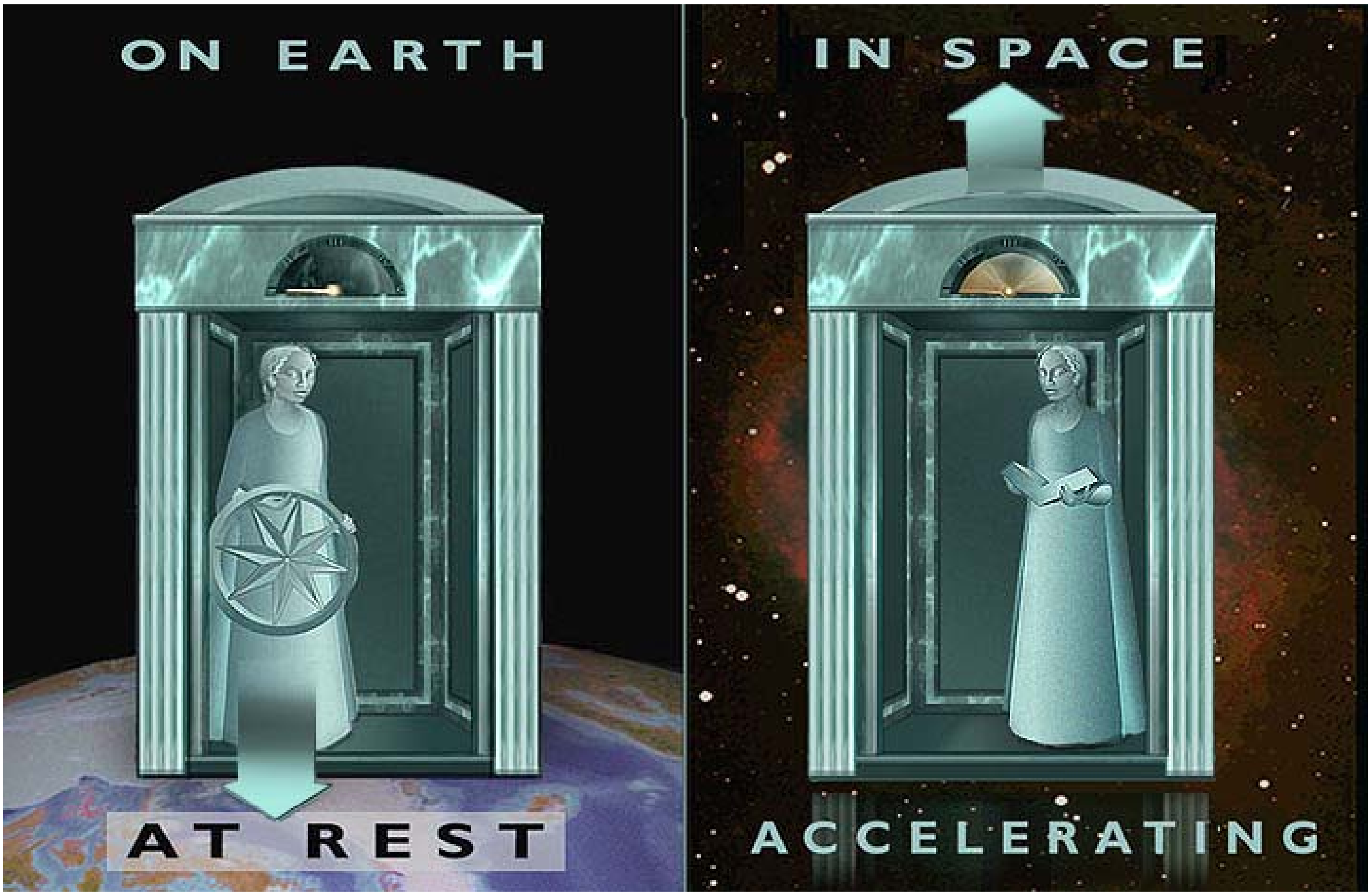
Special relativity and $E=mc^2$ led to the most powerful unification of physical concepts since the time of Newton. The previously separate ideas of space, time, energy and mass were linked by special relativity, although without a clear understanding of how they were linked.



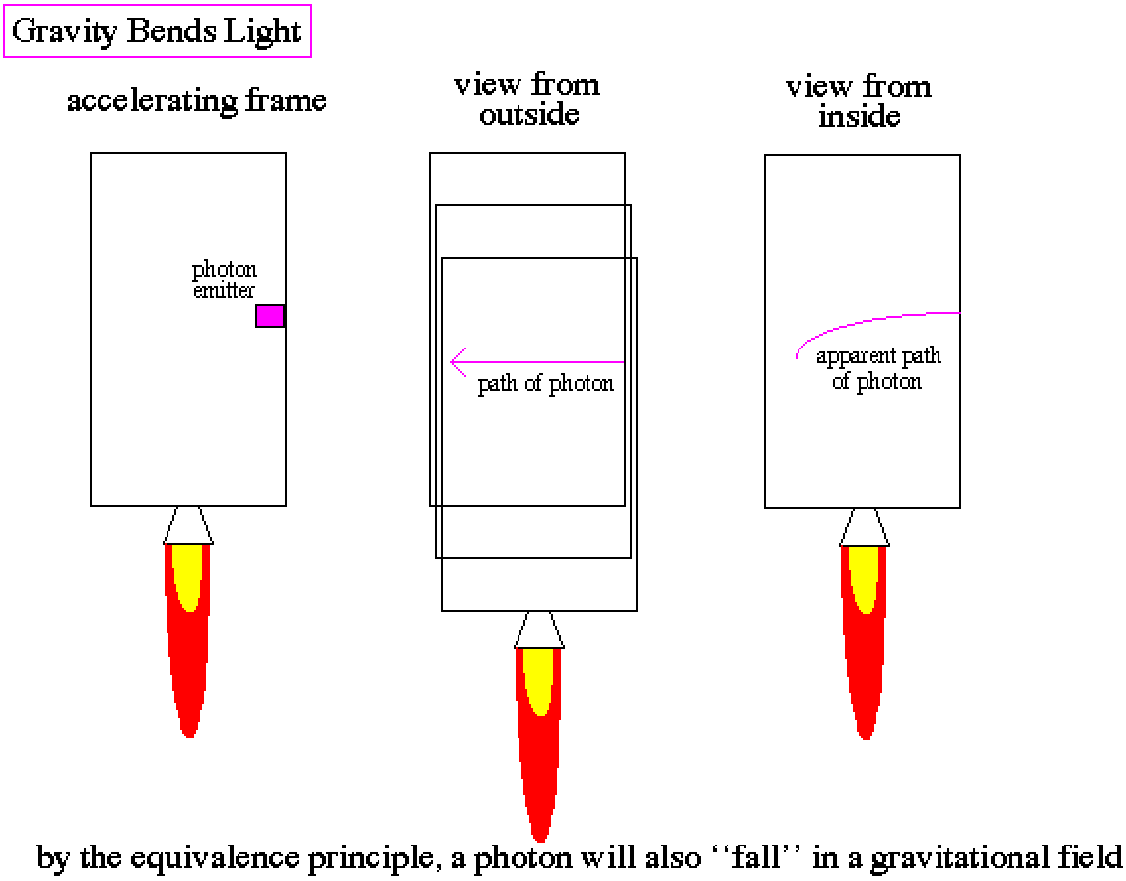

The how and why remained to the domain of what is called general relativity, a complete theory of gravity using the geometry of spacetime. The origin of general relativity lies in Einstein's attempt to apply special relativity in accelerated frames of reference. Remember that the conclusions of relativity were founded for inertial frames, i.e. ones that move only at a uniform velocity. Adding acceleration was a complication that took Einstein 10 years to formulate.

Equivalence Principle:

The equivalence principle was Einstein's `Newton's apple' insight to gravitation. His thought experiment was the following, imagine two elevators, one at rest of the Earth's surface, one accelerating in space. To an observer inside the elevator (no windows) there is no physical experiment that he/she could perform to differentiate between the two scenarios.




An immediate consequence of the equivalence principle is that gravity bends light. To visualize why this is true imagine a photon crossing the elevator accelerating into space. As the photon crosses the elevator, the floor is accelerated upward and the photon appears to fall downward. The same must be true in a gravitational field by the equivalence principle.

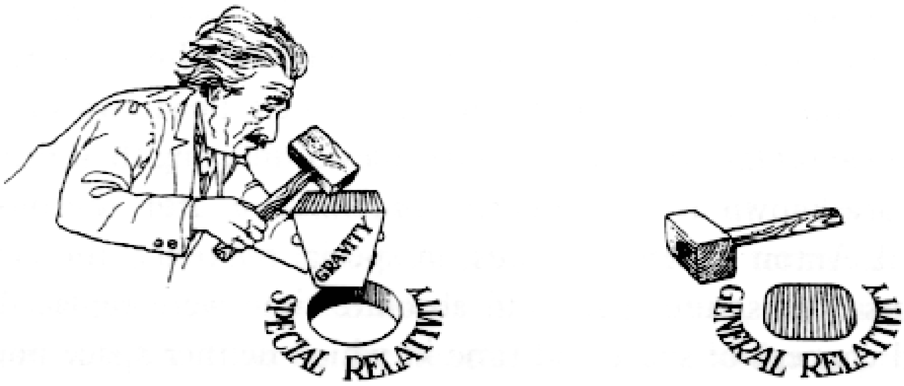


The principle of equivalence renders the gravitational field fundamentally different from all other force fields encountered in nature. The new theory of gravitation, the general theory of relativity, adopts this characteristic of the gravitational field as its foundation.

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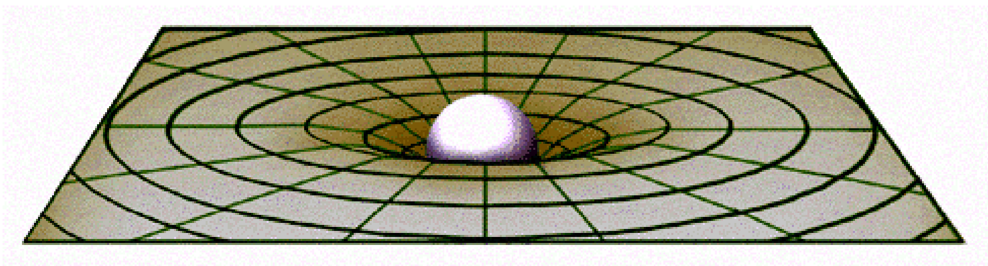
General Relativity :

The second part of relativity is the theory of general relativity and lies on two empirical findings that he elevated to the status of basic postulates. The first postulate is the relativity principle: local physics is governed by the theory of special relativity. The second postulate is the equivalence principle: there is no way for an observer to distinguish locally between gravity and acceleration.



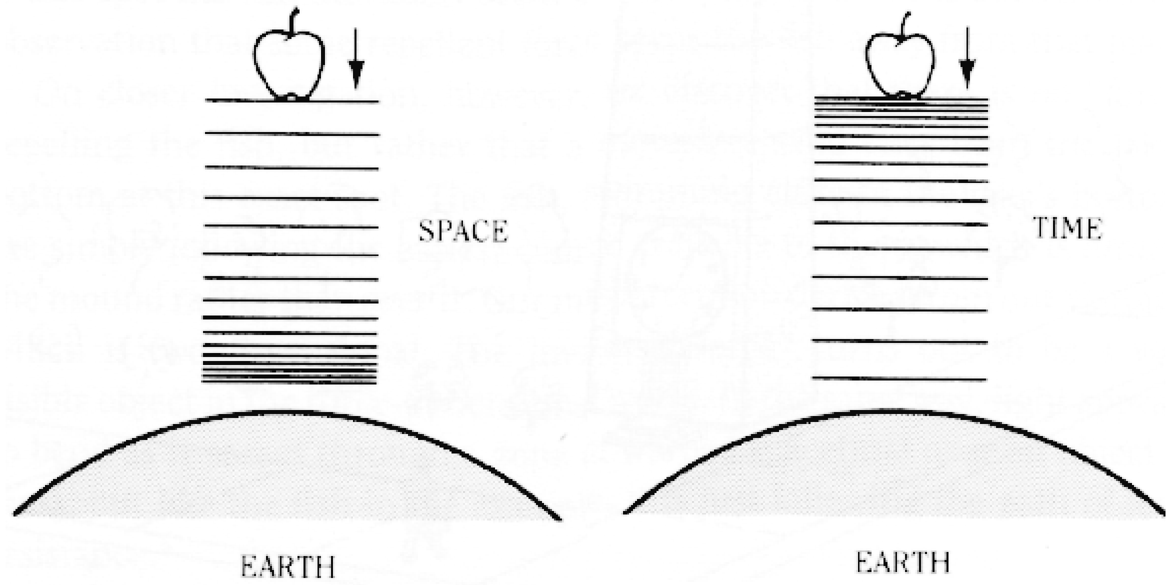

Einstein managed to fit a square peg into a round hole by modifying both the peg and the hole! His general theory of relativity resolved conflicts between Newton's theory of gravity and the special theory of relativity.

Einstein discovered that there is a relationship between mass, gravity and spacetime. Mass distorts spacetime, causing it to curve.



Gravity can be described as motion caused in curved spacetime .

Thus, the primary result from general relativity is that gravitation is a purely geometric consequence of the properties of spacetime. Special relativity destroyed classical physics view of absolute space and time, general relativity dismantles the idea that spacetime is described by Euclidean or plane geometry. In this sense, general relativity is a field theory, relating Newton's law of gravity to the field nature of spacetime, which can be curved.

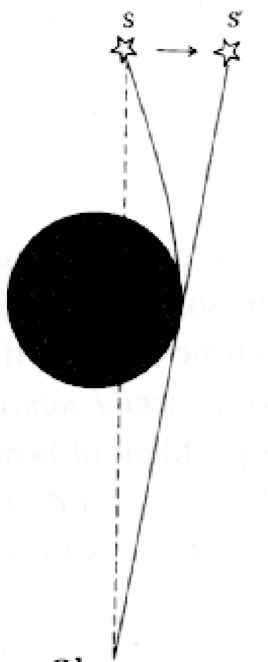



Space contracts near mass and dilates away from it.

Time dilates near mass and contracts away from it.

Gravity in general relativity is described in terms of curved spacetime. The idea that spacetime is distorted by motion, as in special relativity, is extended to gravity by the equivalence principle. Gravity comes from matter, so the presence of matter causes distortions or warps in spacetime. Matter tells spacetime how to curve, and spacetime tells matter how to move (orbits).

There were two classical test of general relativity, the first was that light should be deflected by passing close to a massive body. The first opportunity occurred during a total eclipse of the Sun in 1919.




Measurements of stellar positions near the darkened solar limb proved Einstein was right. Direct confirmation of gravitational lensing was obtained by the Hubble Space Telescope last year.

The second test is that general relativity predicts a time dilation in a gravitational field, so that,

relative to someone outside of the field, clocks (or atomic processes) go slowly. This was confirmed with atomic clocks flying airplanes in the mid-1970's.

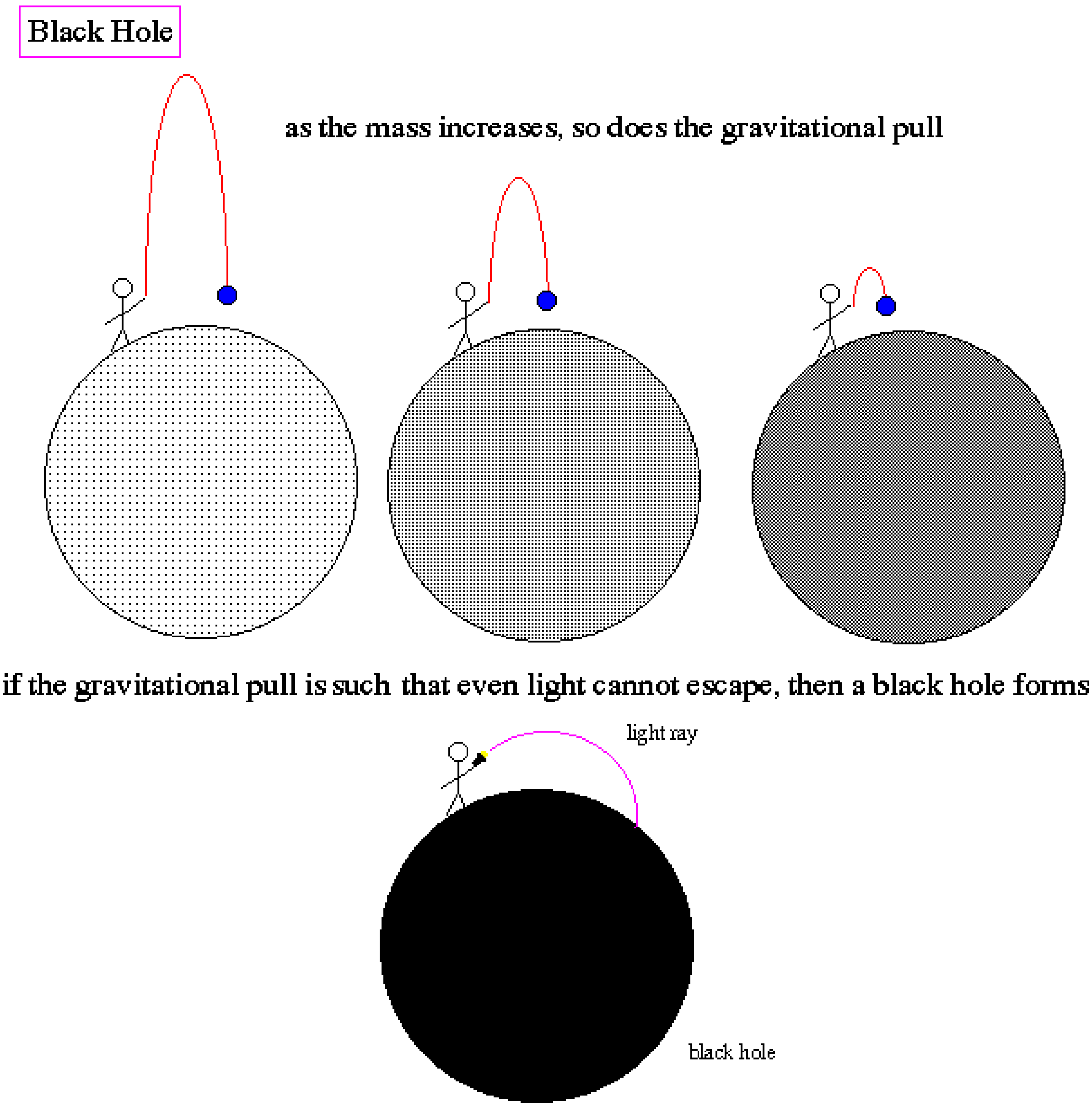
The general theory of relativity is constructed so that its results are approximately the same as those of Newton's theories as long as the velocities of all bodies interacting with each other gravitationally are small compared with the speed of light--i.e., as long as the gravitational fields involved are weak. The latter requirement may be stated roughly in terms of the escape velocity. A gravitational field is considered strong if the escape velocity approaches the speed of light, weak if it is much smaller. All gravitational fields encountered in the solar system are weak in this sense.

Notice that at low speeds and weak gravitational fields, general and special relativity reduce to Newtonian physics, i.e. everyday experience.

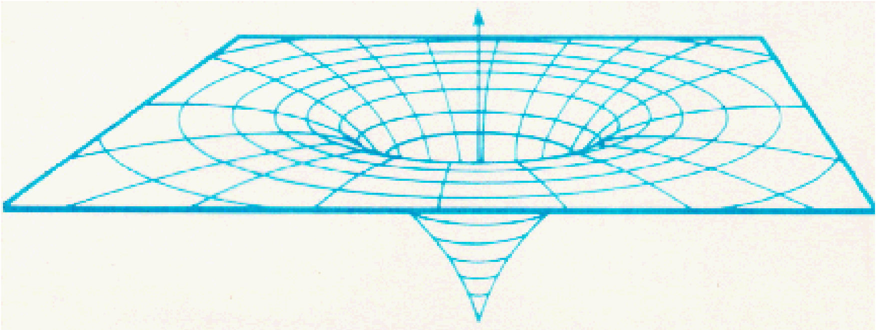
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Black Holes:

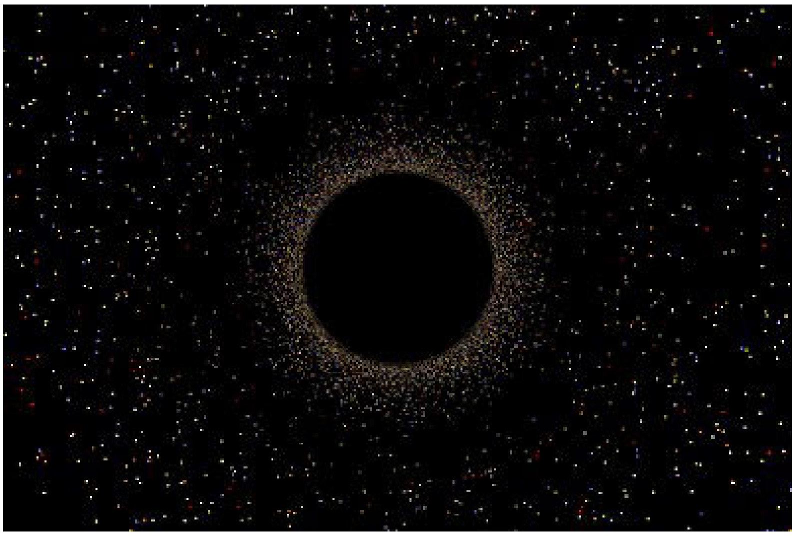
The fact that light is bent by a gravitational field brings up the following thought experiment. Imagine adding mass to a body. As the mass increases, so does the gravitational pull and objects require more energy to reach escape velocity. When the mass is sufficiently high enough that the velocity needed to escape is greater than the speed of light we say that a black hole has been created.



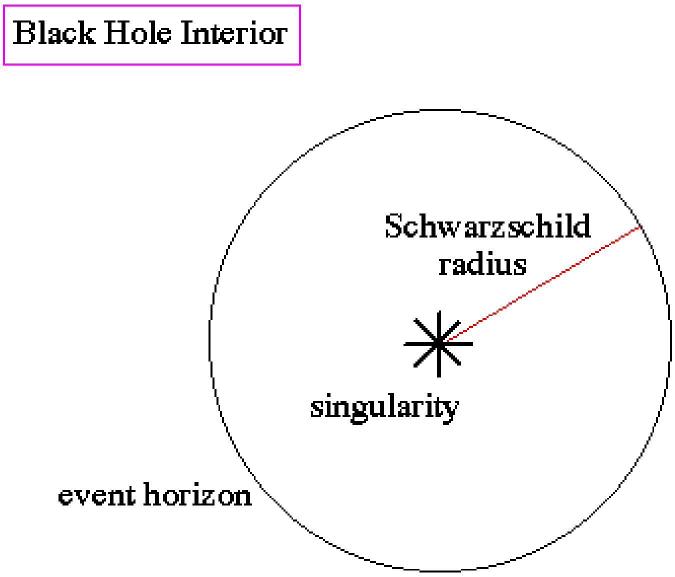
Another way of defining a black hole is that for a given mass, there is a radius where if all the mass is compress within this radius the curvature of spacetime becomes infinite and the object is surrounded by an event horizon. This radius called the Schwarzschild radius and varys with the mass of the object (large mass objects have large Schwarzschild radii, small mass objects have small Schwarzschild radii).



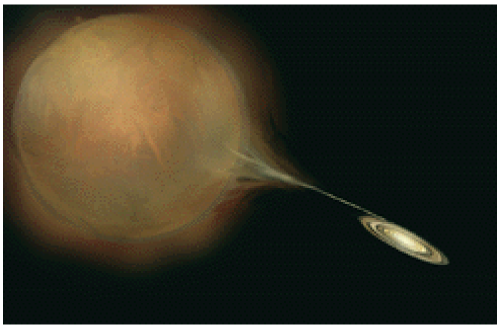
The Schwarzschild radius marks the point where the event horizon forms, below this radius no light escapes. The visual image of a black hole is one of a dark spot in space with no radiation emitted. Any radiation falling on the black hole is not reflected but rather absorbed, and starlight from behind the black hole is lensed.



Even though a black hole is invisible, it has properties and structure. The boundary surrounding the black hole at the Schwarzschild radius is called the event horizon, events below this limit are not observed. Since the forces of matter can not overcome the force of gravity, all the mass of a black hole compresses to infinity at the very center, called the singularity.

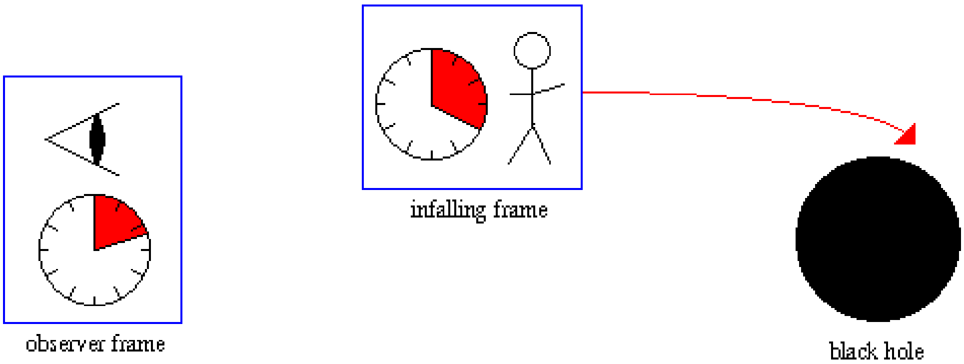



A black hole can come in any size. Stellar mass black holes are thought to form from supernova events, and have radii of 5 km. Galactic black hole in the cores of some galaxies, millions of solar masses and the radius of a solar system, are built up over time by cannibalizing stars. Mini black holes formed in the early Universe (due to tremendous pressures) down to masses of asteroids with radii the size of a grain of sand.

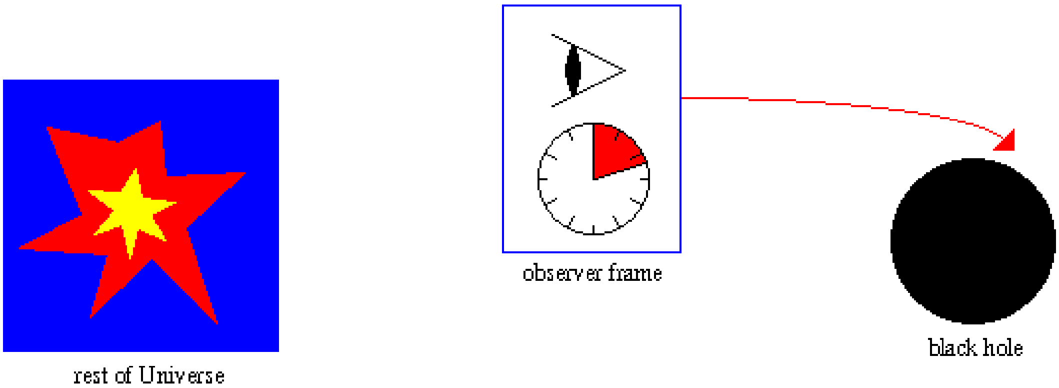


Note that a black hole is the ultimate entropy sink since all information or objects that enter a black hole never return. If an observer entered a black hole to look for the missing information, he/she would be unable to communicate their findings outside the event horizon.

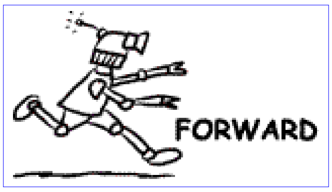
# Falling into a Black Hole




the outside observer watchs the infalling's frame clock slow until it freezes just above the event horizon




on the other hand, the infalling observer sees the rest of the Universe speeding up, watching the end of time just before falling into the event horizon

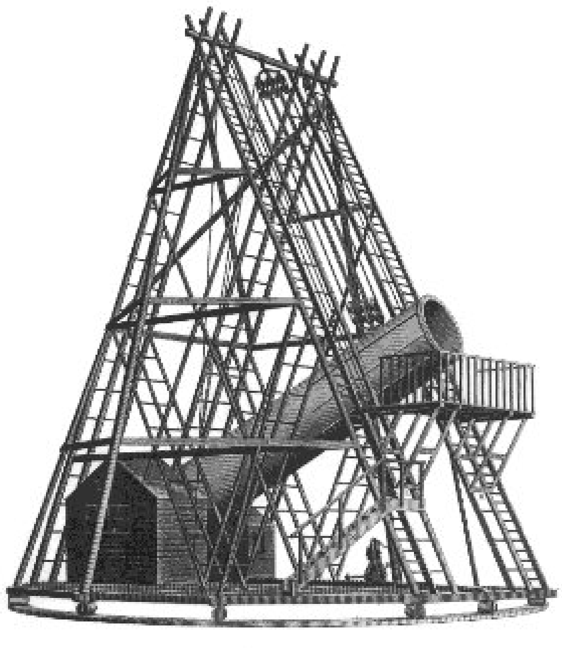





Galaxies:

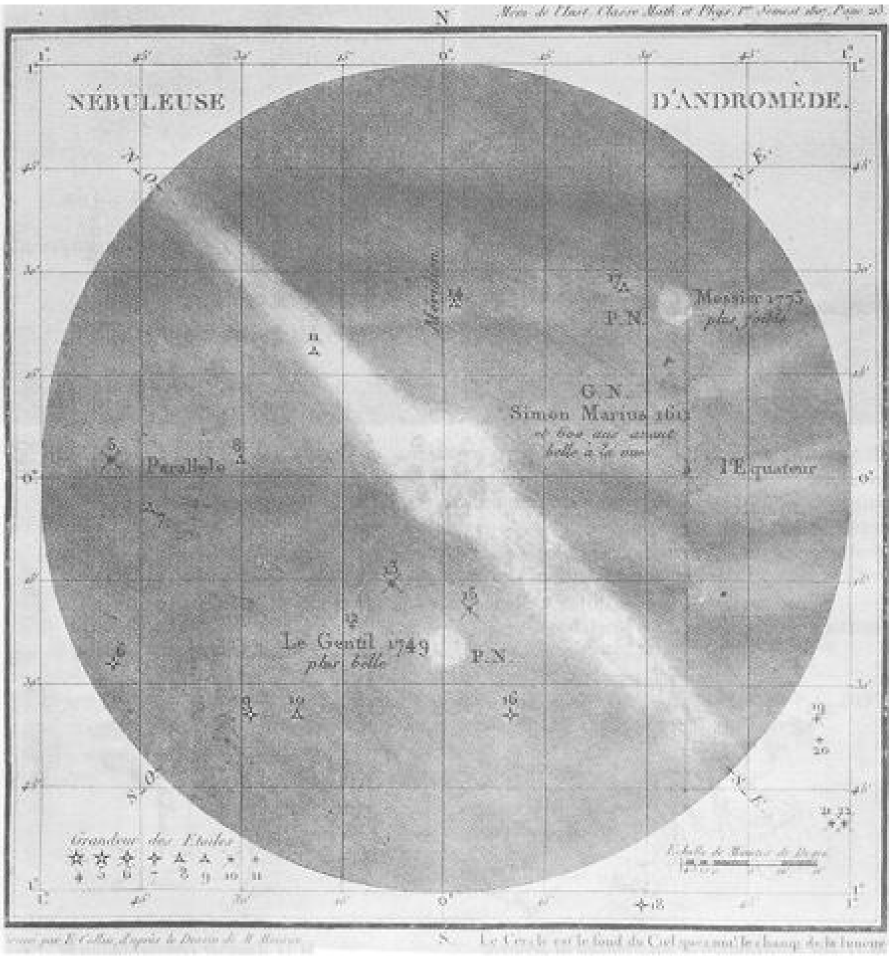
A galaxy is a collect of stars, gas and dust bound together by their common gravitational pull. Galaxies range from 10,000 to 200,000 light-years in size and between $10^9$ and $10^{14}$ solar luminosities in brightness.

The discovery of `nebula', fuzzy objects in the sky that were not planets, comets or stars, is attributed to Charles Messier in the late 1700's. His collection of 103 objects is the first galaxy catalog. Herschel (1792-1871) used a large reflecting telescope to produce the first General Catalog of galaxies.

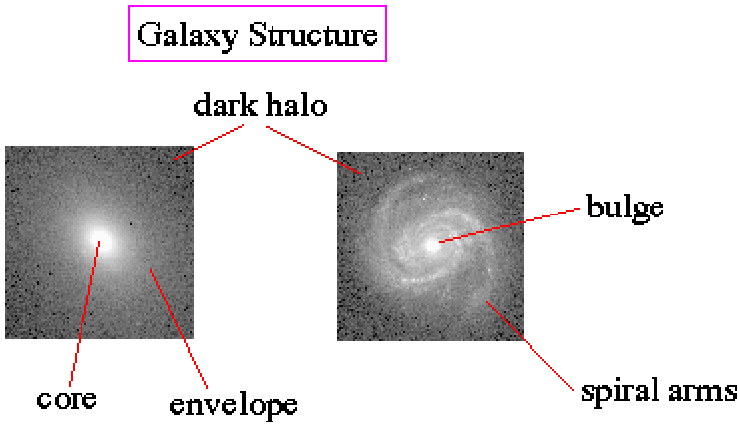


Before photographic plates, galaxies were drawn by hand by the astronomer.

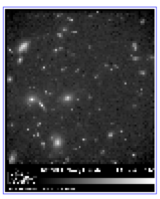





Galaxies have certain features in common. Gravity holds the billions of stars together, and the densest region is in the center, called a core or bulge. Some galaxies have spiral or pinwheel arms. All galaxies have a faint outer region or envelope and a mysterious dark matter halo.

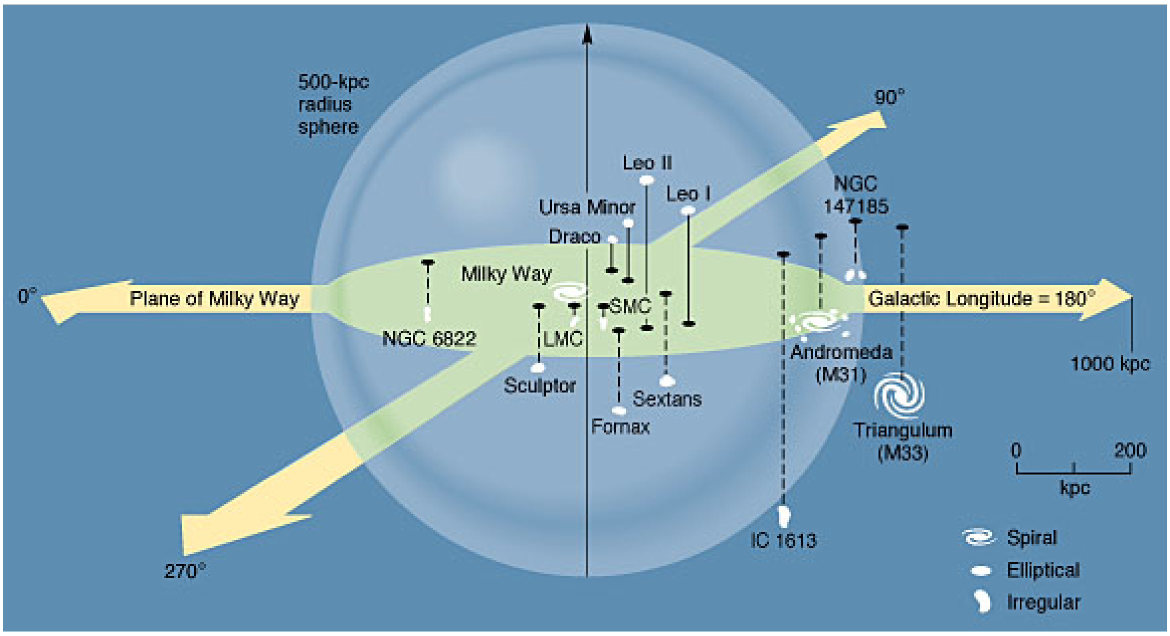



The contents of galaxies vary from galaxy type to galaxy type, and with [time](#).



Almost all galaxy types can be found in [groups](#) or [clusters](#). Many clusters of galaxies have a large,

supergiant galaxy at its center which has grow by cannibalizing its neighbors. Our solar system is located in outer regions of a spiral galaxy we call the Milky Way. The nearest neighbor galaxy is Andromeda Galaxy (M31).

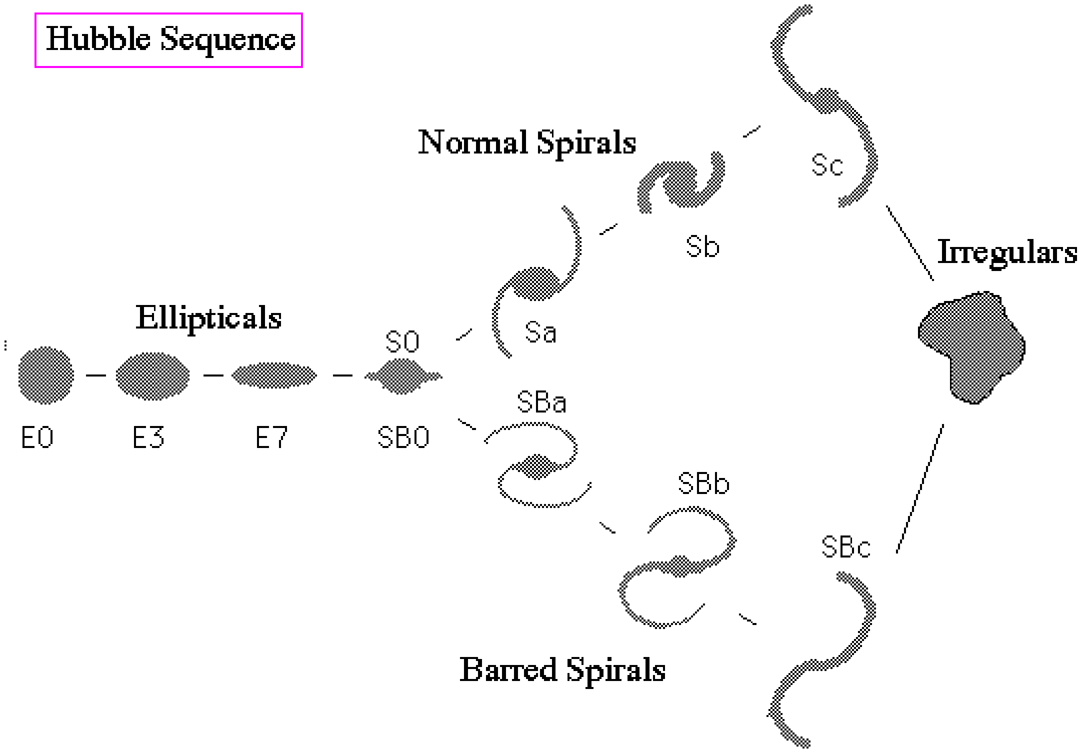



Above is a 3D plot of most of the Local Group of galaxies, the population of galaxies within 1000 kpc if the Milky Way. Clustering of dwarf satellite galaxies around the great Milky Way and Andromeda spirals can be seen.

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Hubble sequence :

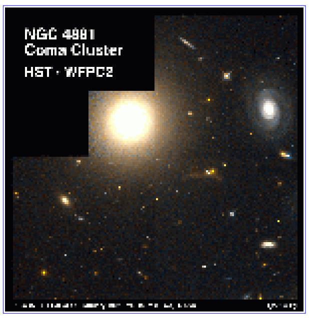
Almost all current systems of galaxy classification are outgrowths of the initial scheme proposed by American astronomer Edwin Hubble in 1926. In Hubble's scheme, which is based on the optical appearance of galaxy images on photographic plates, galaxies are divided into three general classes: ellipticals, spirals, and irregulars.




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Elliptical galaxies :

Galaxies of this class have smoothly varying brightnesses, steadily decreasing outward from the center. They appear elliptical in shape, with lines of equal brightness made up of concentric and similar ellipses. These galaxies are nearly all of the same color: they are somewhat redder than the Sun. Ellipticals are also devoid of gas or dust and contain just old stars.




NGC 4881

All ellipticals look alike, NGC 4881 is a good example (NGC stands for New General Catalog). Notice how smooth and red NGC 4881 looks compared to the blue spirals to the right.



M32

A few ellipticals are close enough to us that we can resolve the individual stars within them, such as M32, a companion to the Andromedia Galaxy.

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Spiral galaxies :

These galaxies are conspicuous for their spiral-shaped arms, which emanate from or near the nucleus and gradually wind outward to the edge. There are usually two opposing arms arranged symmetrically around the center. The nucleus of a spiral galaxy is a sharp-peaked area of smooth texture, which can be quite small or, in some cases, can make up the bulk of the galaxy. The arms are embedded in a thin disk of stars. Both the arms and the disk of a spiral system are blue in color, whereas its central areas are red like an elliptical galaxy.



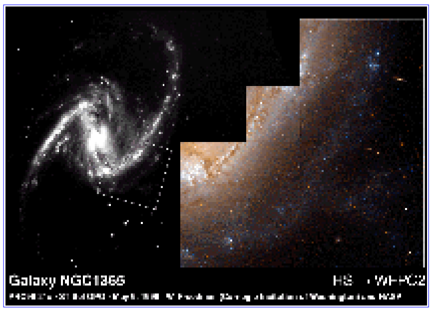
M100

Notice in the above picture of M100 from HST, that the center of the spiral is red/yellow and the arms are blue. Hotter, younger stars are blue, older, cooler stars are red. Thus, the center of a spiral is made of old stars, with young stars in the arms formed recently out of gas and dust.



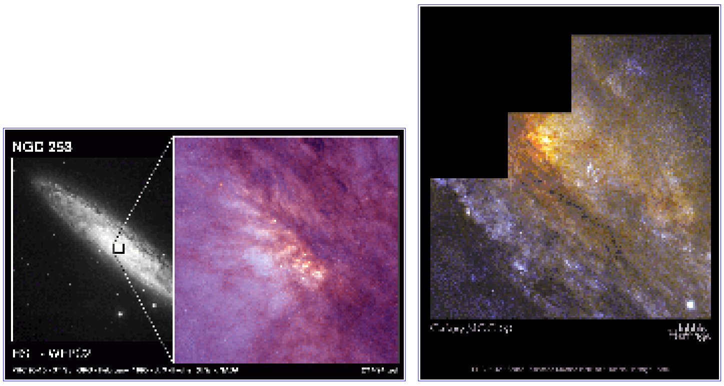

NGC 4639

The bulge of NGC 4639 is quite distinct from the younger, bluer disk regions.




NGC 1365

NGC 1365 is a barred spiral galaxy. Note the distinct dark lanes of obscuring dust in the bar pointing towards the bulge. A close-up of the spiral arms shows blue nebula, sites of current star formation.



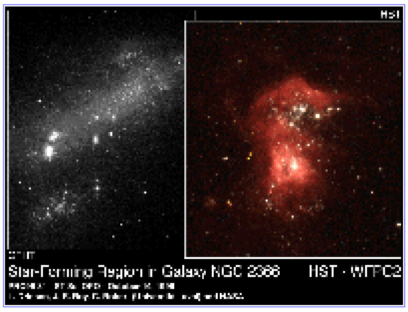

NGC 253 core and outer disk

NGC 253 is a typical Sa type galaxy with very tight spiral arms. As spiral galaxies are seen edge-on the large amount of gas and dust is visible as dark lanes and filaments crossing in front of the bulge regions.

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Irregular galaxies :

Most representatives of this class consist of grainy, highly irregular assemblages of luminous areas. They have no noticeable symmetry nor obvious central nucleus, and they are generally bluer in color than are the arms and disks of spiral galaxies.



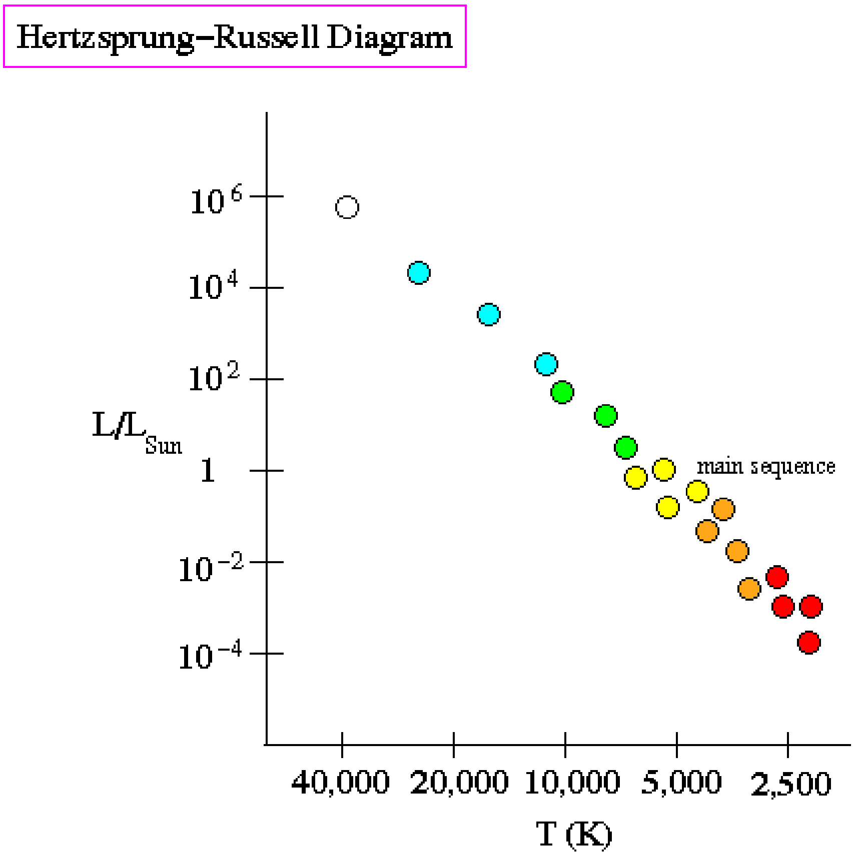

NGC 2363

NGC 2363 is an example of a nearby irregular galaxy. There is no well defined shape to the galaxy, nor are there spiral arms. A close-up of the bright region on the east side shows a cluster of new stars embedded in the red glow of ionized hydrogen gas.

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Galaxy Colors:

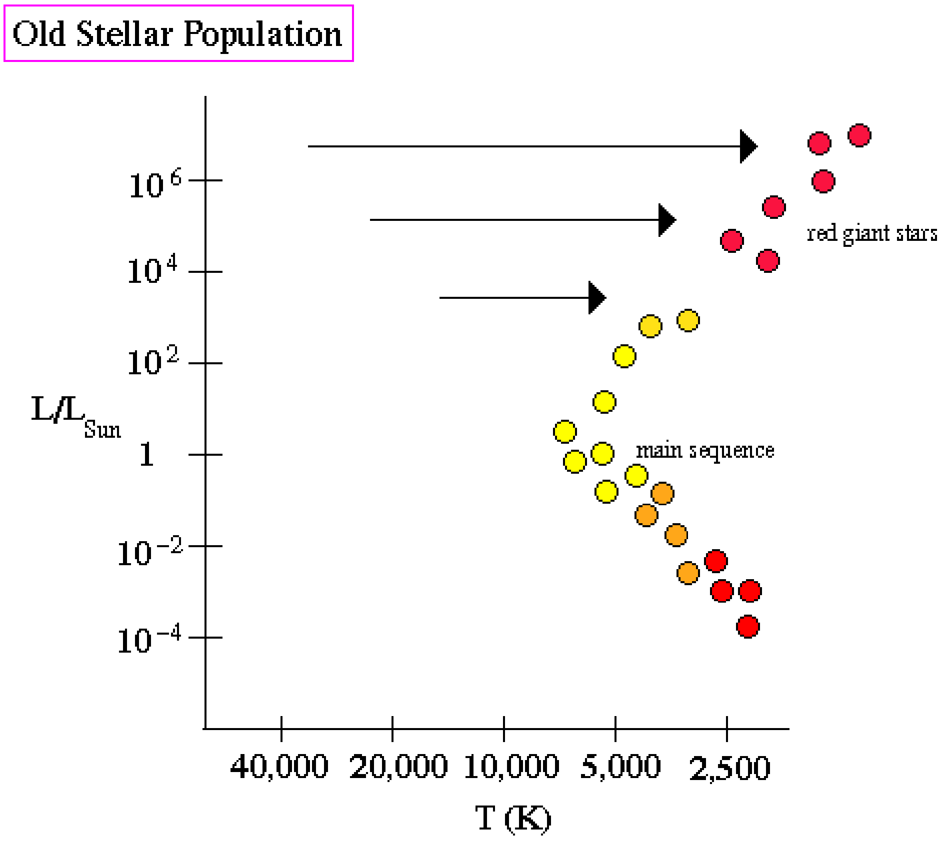
The various colors in a galaxy (red bulge, blue disks) is due to the types of stars found in those galaxy regions, called its stellar population. Big, massive stars burn their hydrogen fuel, by thermonuclear fusion, extremely fast. Thus, they are bright and hot = blue. Low mass stars, although more numerous, are cool in surface temperature (= red) and much fainter. All this is displayed in a Hertzsprung-Russell Diagram of the young star cluster.




the HR diagram is a plot of stellar luminosity (with respect to the Sun) versus stellar temperature (color). Various types of stars occupy certain parts of the diagram.

A new cluster of stars will be composed of a range of stellar masses, which means a range of stellar colors -> brightnesses

The hot blue stars use their core fuel much faster than the fainter, cooler red stars. Therefore, a young stellar population has a mean color that is blue (the sum of the light from all the stars in the stellar population) since most of the light is coming from the hot stars. An old stellar population is red, since all the hot stars have died off (turned into red giant stars) leaving the faint cool stars.



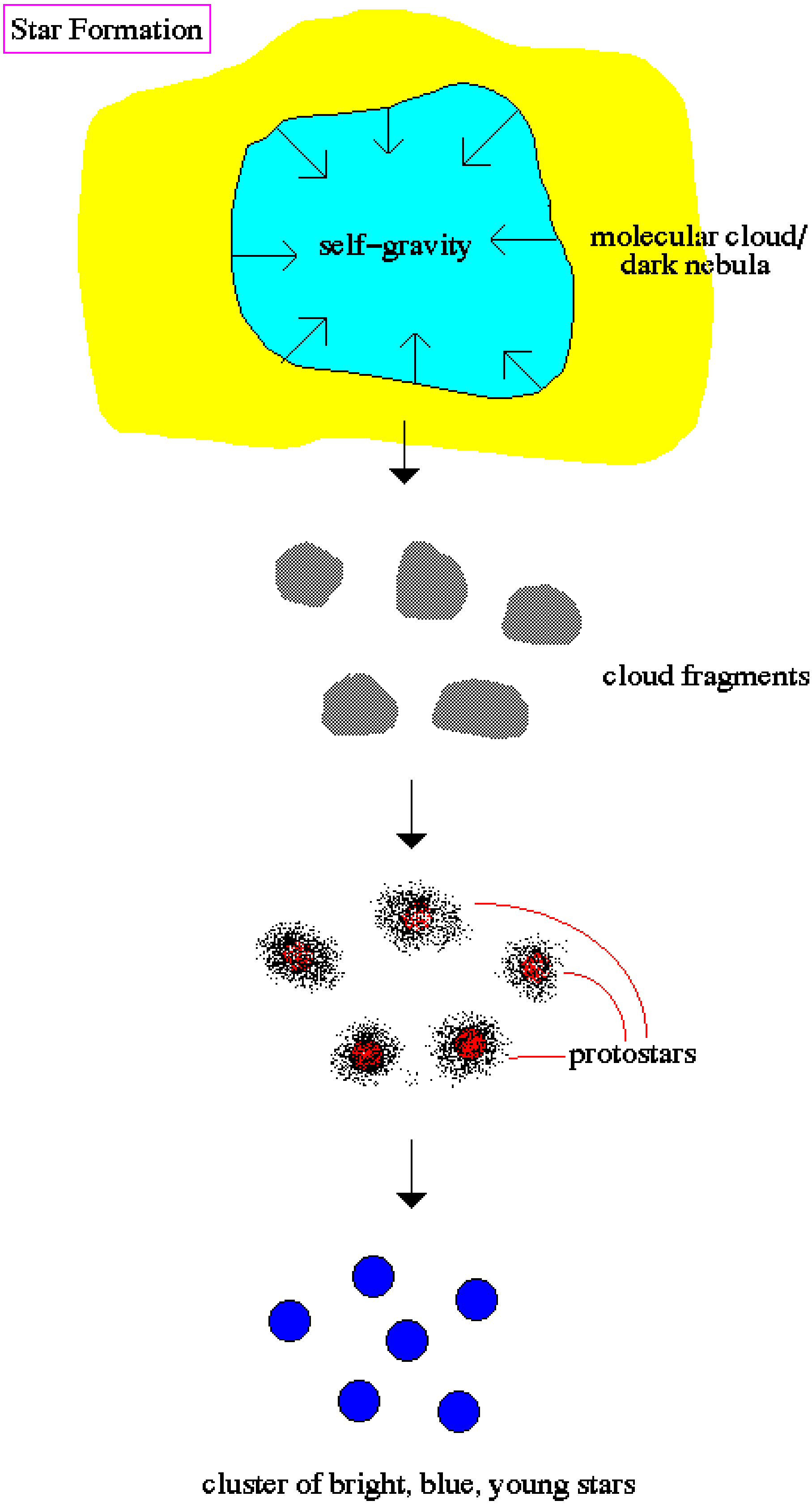

Over billions of years, bright blue stars evolve across the HR diagram to become red giant stars. The integrated color of the once blue young stellar population, becomes red as the red giants stars dominate.

The bottom line is that the red regions of a galaxy are old, with no hot stars. The blue portions of a galaxy are young, meaning the stellar population that dominates this region is newly formed.

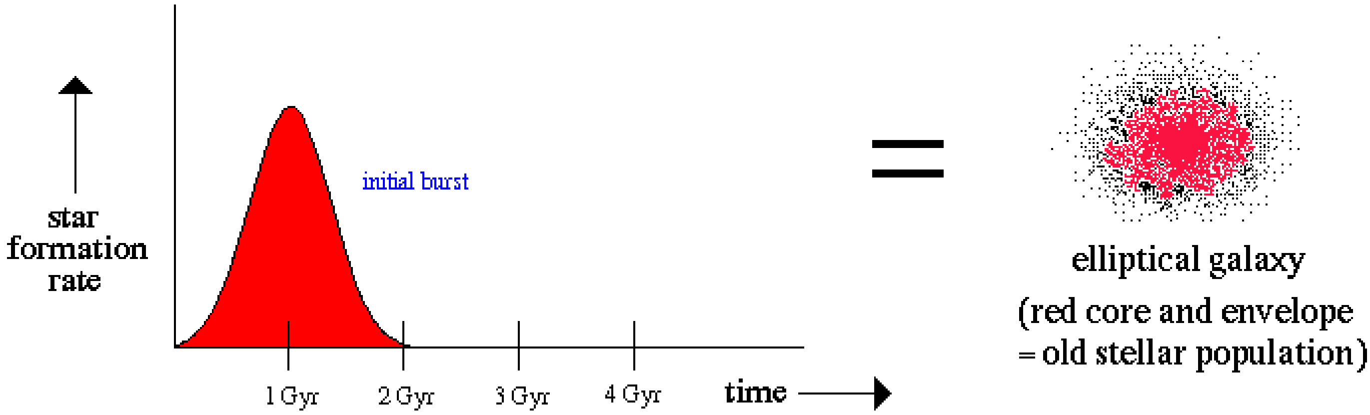
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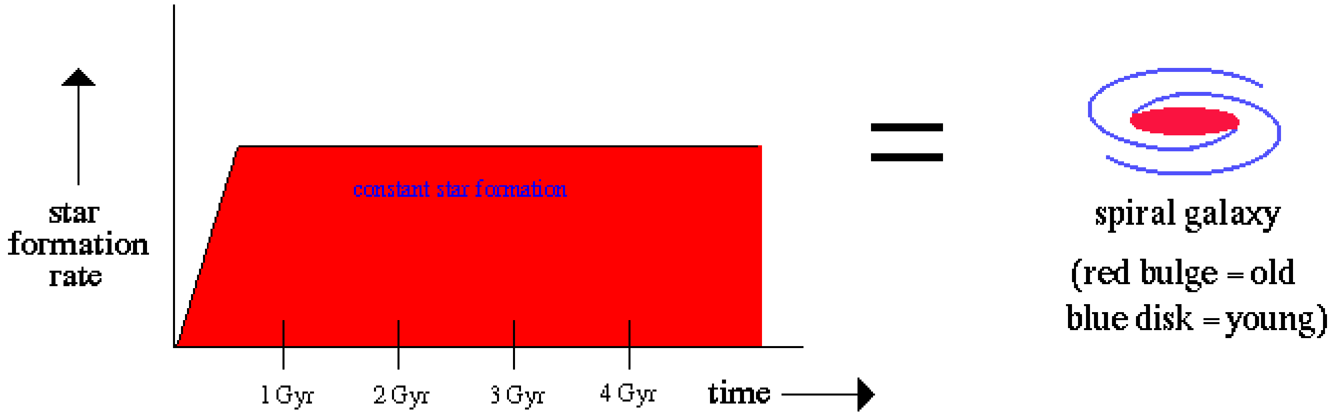
Star Formation :

The one feature that correlates with the shape, appearance and color of a galaxy is the amount of current star formation. Stars form when giant clouds of hydrogen gas and dust collapse under their own gravity. As the cloud collapses it fragments into many smaller pieces, each section continues to collapse until thermonuclear fusion begins.



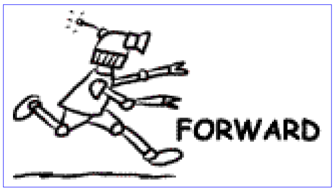

Initial conditions for a galaxy determines its rate of star formation. For example, elliptical galaxies collapse early and form stars quickly. The gas is used up in its early years and today has the appearance of a smooth, red object with no current star formation.




Spirals, on the other hand, form slower, with lower rates of star formation. The gas that `fuels' star formation is used slower and, thus, there is plenty around today to continue to form stars within the spiral arms.

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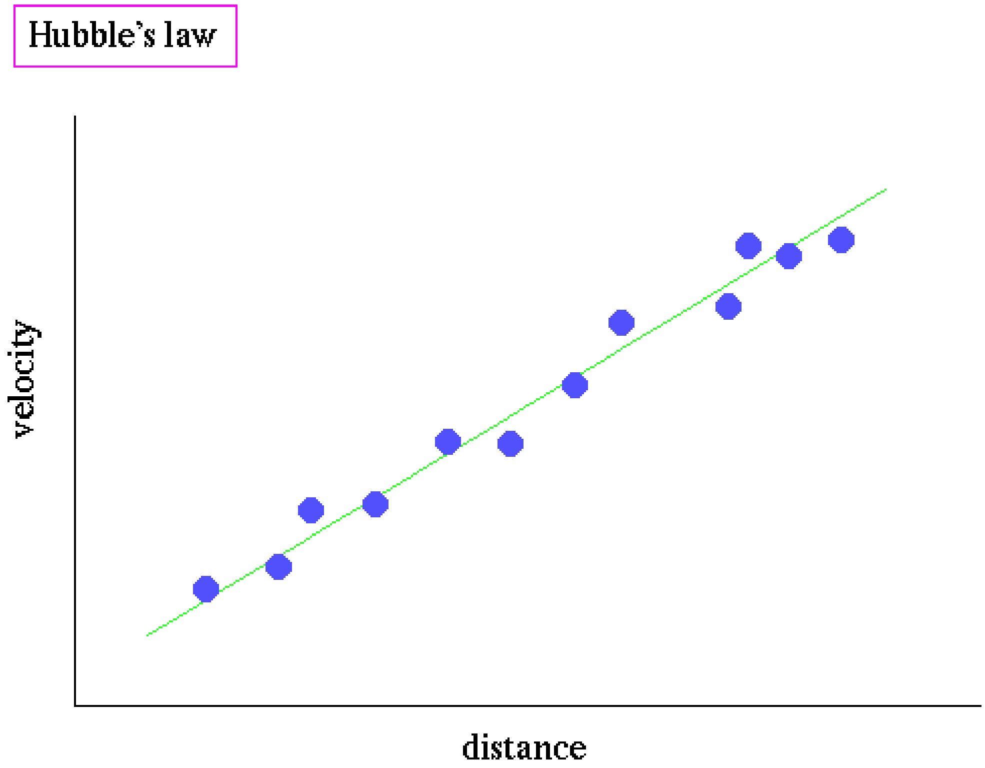



Chapter 24 of Hartman and Impey



Hubble's law:

In the 1930's, Edwin Hubble discoveried that all galaxies have a positive redshift. In other words, all galaxies were receding from the Milky Way. By the Copernican principle (we are not at a special place in the Universe), we deduce that all galaxies are receding from each other, or we live in a dynamic, expanding Universe.

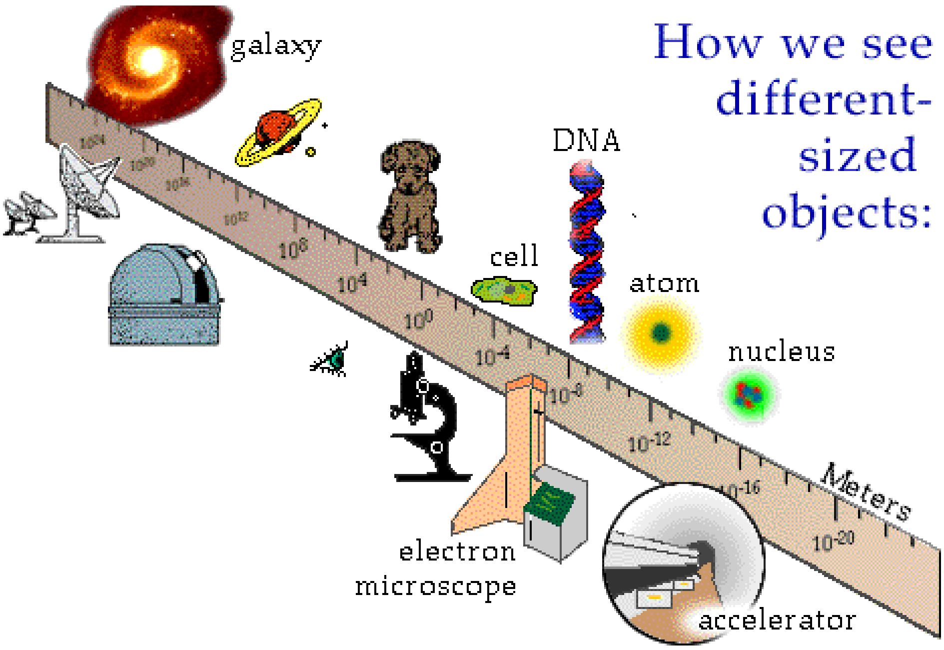



The expansion of the Universe is described by a very simple equation called Hubble's law; the velocity of the recession of a galaxy is equal to a constant times its distance (v=Hd). Where the constant is called Hubble's constant and relates distance to velocity in units of light-years.

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Distance Scale:

The most important value for an astronomical object is its distance from the Earth. Since cosmology deals with objects larger and brighter than our Sun or solar system, it is impossible to have the correct frame of reference with respect to their size and luminosity as there is nothing to compare extragalactic objects with.




Before the 1920's, it was thought that galaxies were in fact objects within our own Galaxy, possibly regions forming individual stars. They were given the name ``nebula'', which we now use to denote regions of gas and dust within galaxies.

At the turn of the century Cepheid variable stars, a special class of pulsating stars that exhibit a particular period-luminosity relation, were discovered. In other words, it was found that their intrinsic brightness was proportional to their period of variation and, hence, could be used for measuring the distances to nearby galaxies.

In the late 1920's, Hubble discovered similar Cepheid stars in neighboring galaxies as was found in our own Galaxy. Since they followed the same period-luminosity relation, and they were very faint, then this implied that the neighboring galaxies were very far away. This proved that spiral `nebula' were, in fact, external to our own Galaxy and sudden the Universe was vast in space and time.

Although Hubble showed that spiral nebula were external to our Galaxy, his estimate of their distances was off by a factor of 6. This was due to the fact that the calibration to Cepheids was poor at the time, combined with the primitive telescopes Hubble used.

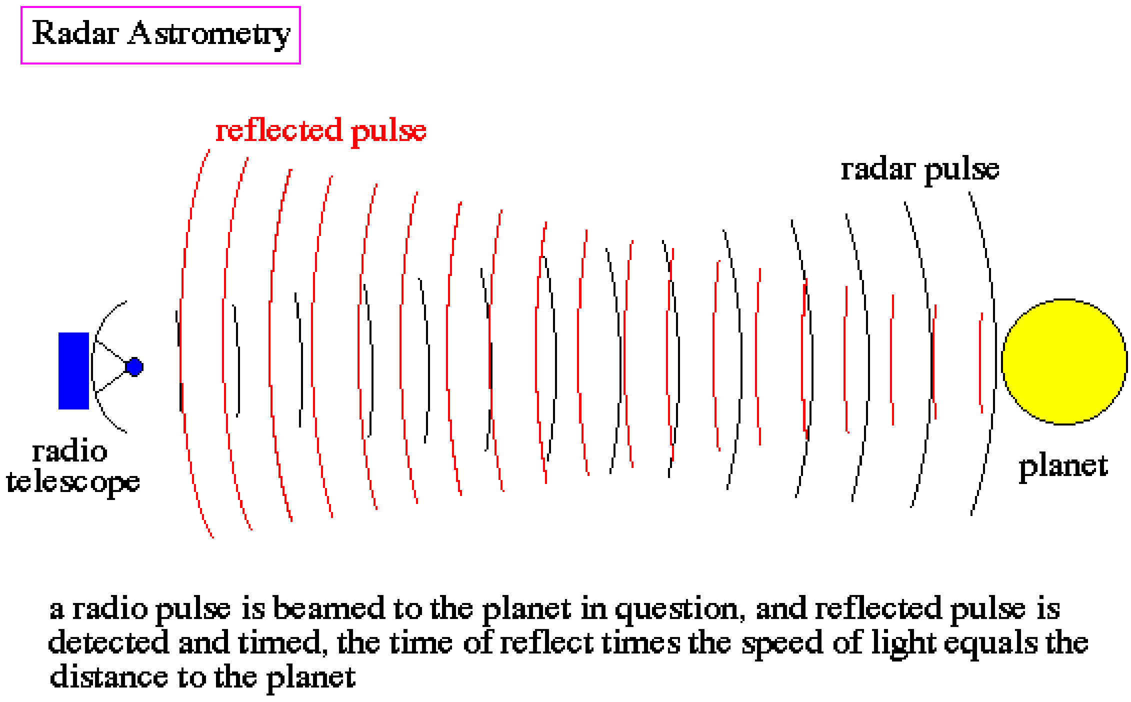
Modern efforts to obtain an estimate of Hubble's constant, the expansion rate of the Universe, find it necessary to determine the distance and the velocities of a large sample of galaxies. The hardest step in this process is the construct of the distance scale for galaxies, a method of determining the true distance to a particular galaxy using some property or characteristic that is visible over a range of galaxies types and distance.

The determination of the distance scale begins with the construction of ladder of primary, secondary and tertiary calibrators in the search for a standard candle.

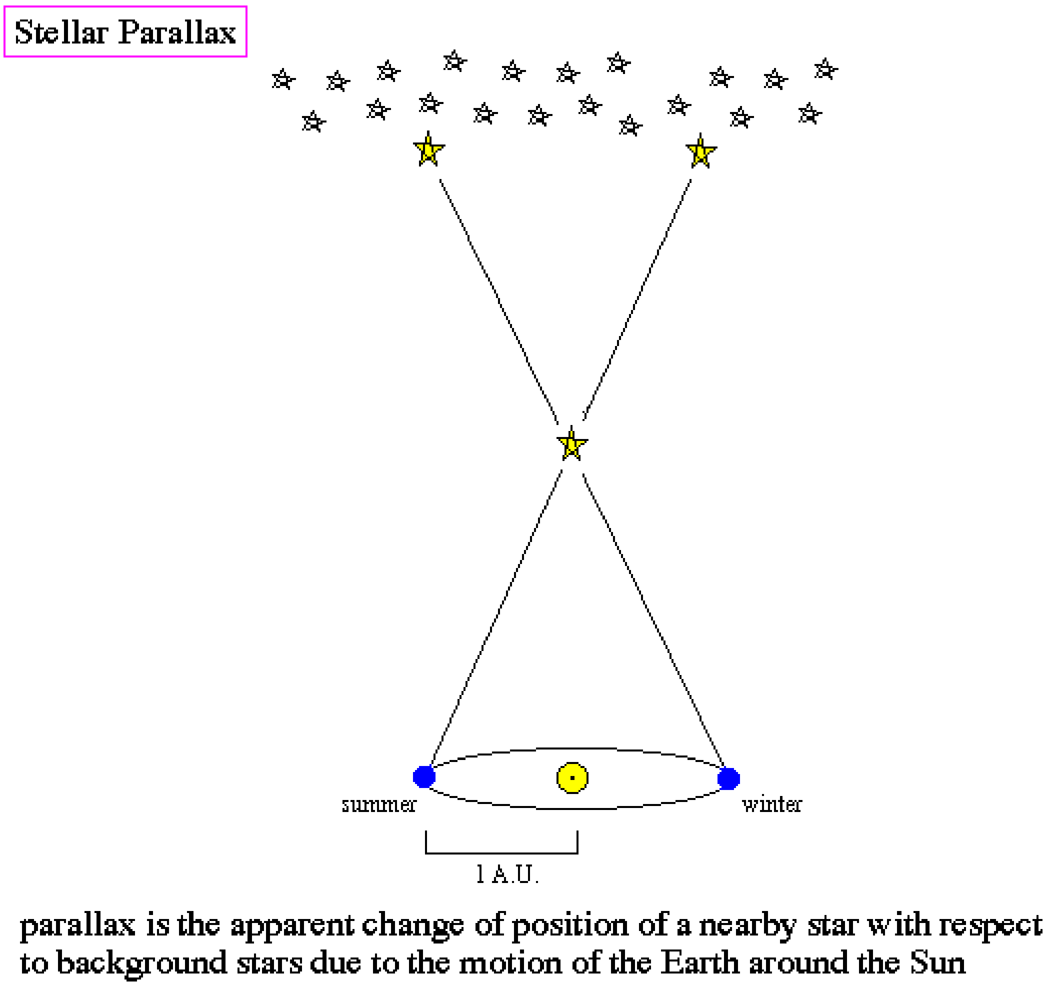
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Primary Calibrators:

The construction of the distance scale ladder is a process of building of a chain of objects with well determined distance. The bottom of this chain is the determination of the scale of objects in the Solar System. This is done through radar ranging, where a radio pulse is reflected off of the various planets in the Solar System.




The most important value from solar system radar ranging is the exact distance of the Earth from the Sun, determined by triangular measurement of the Earth and terrestrial worlds. This allows an accurate value for what is called the Astronomical Unit (A.U.), i.e. the mean Earth-Sun distance. The A.U. is the ``yardstick'' for measuring the distance to nearby stars by parallax.

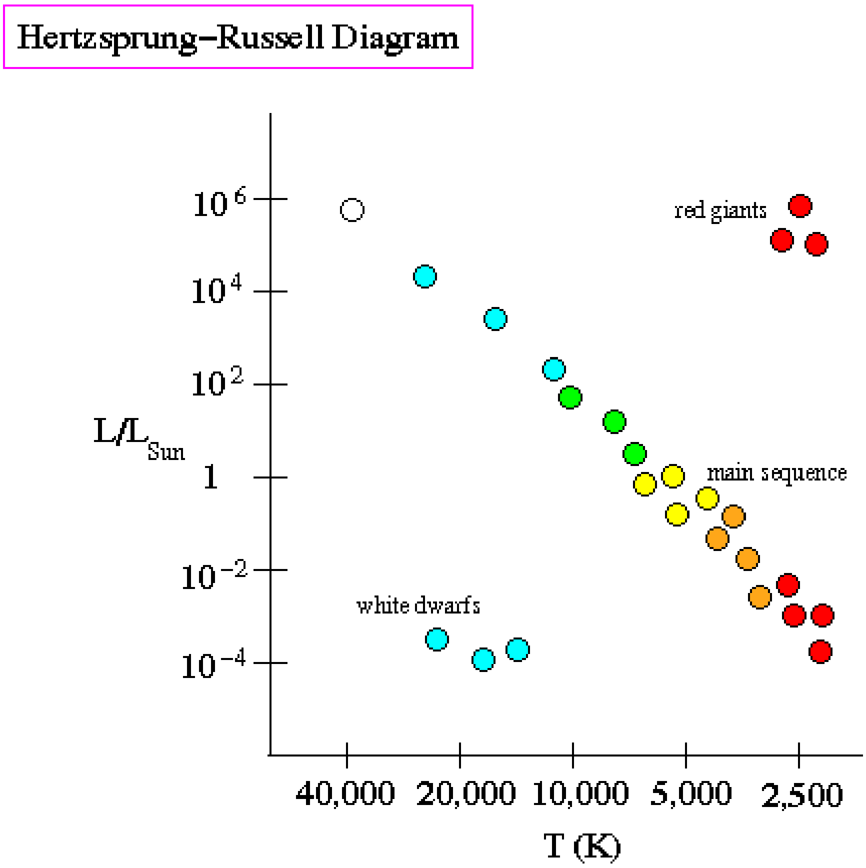


The parallax system is only good for stars within 300 light-years of the Earth due to limitations of measuring small changes in stellar position. Fortunately, there are hundreds of stars within this volume of space, which become the calibrators for secondary distance indicators.

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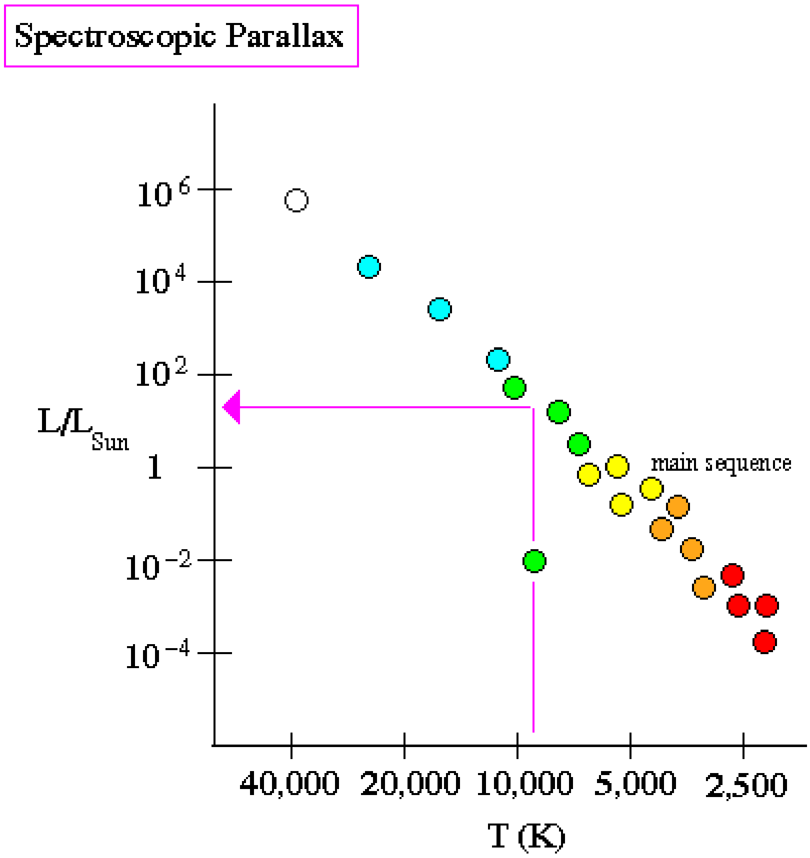
Secondary Calibrators:

Secondary calibrators of the distance scale depend on statistical measures of stellar properties, such as the mean brightness of a class of stars. It has been known since the 1800's that stars follow a particular color-luminosity relation known as the Hertzsprung-Russell Diagram.




the HR diagram is a plot of stellar luminosity (with respect to the Sun) versus stellar temperature (color). Various types of stars occupy certain parts of the diagram. Stars spend most of their lifetimes on the main sequence

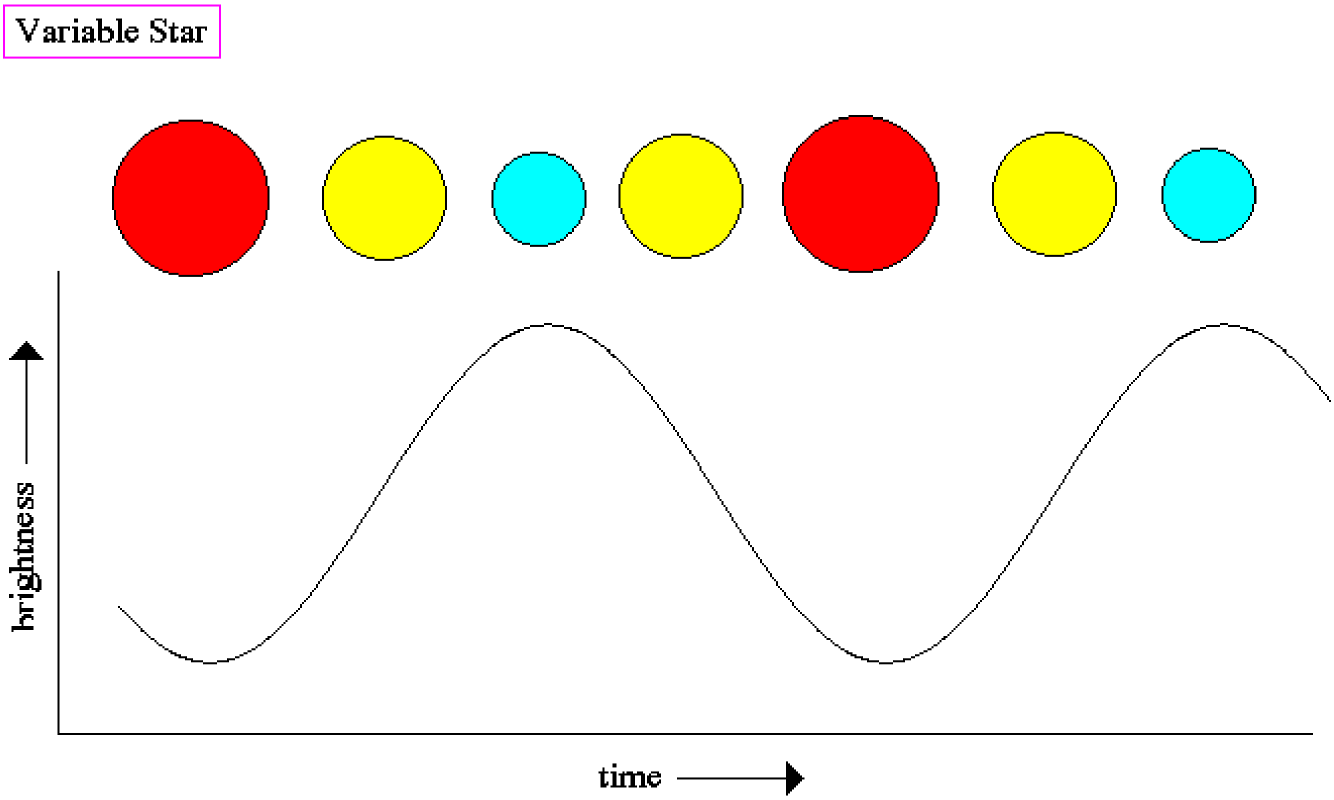
The existence of the main sequence for stars, a relationship between luminosity and color due to the stable, hydrogen-burning part of a star's life, allows for the use of spectroscopic parallax. A stars temperature is determined by its spectrum (some elements become ions at certain temperatures). With a known temperature, then an absolute luminosity can be read off the HR diagram.



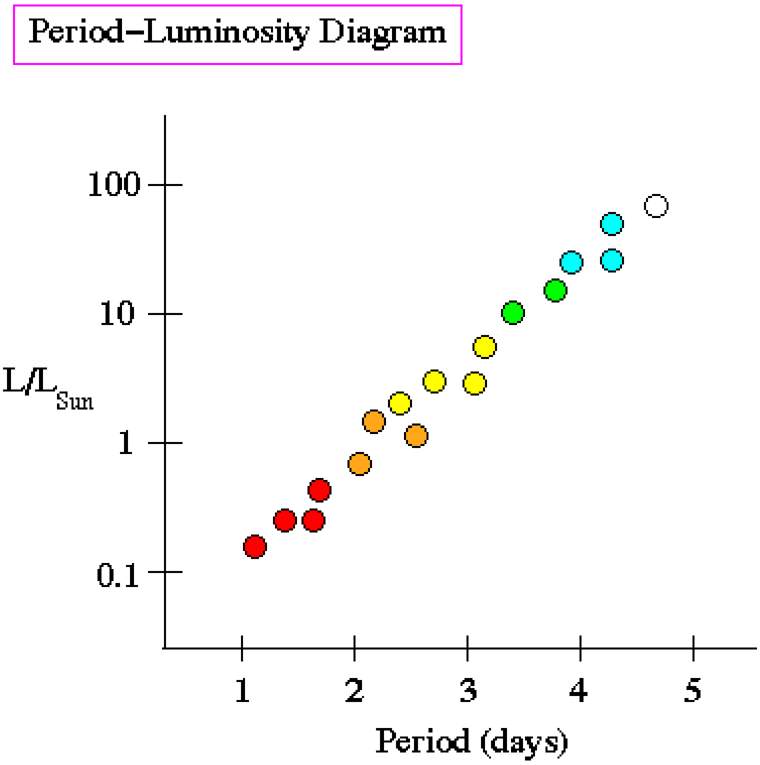

the true brightness of a star can be found if the color is known by matching the star to the main sequence. Knowledge of the observed brightness plus the true brightness derives the distance to the star.

The distance to a star is simply the ratio of its apparent brightness and its true brightness (imagine car headlights at a distance). The method allows us to measure the distances to thousands of local stars and, in particular, to nearby star clusters which harbor variable stars.

A variable star is a star where the brightness of the star changes over time (usually a small amount). This is traced by a light curve, a plot of brightness and time.




Particular variable stars, such as Cepheids, have a period-luminosity relationship. Meaning that for a particular period of oscillation, they have a unique absolute brightness.

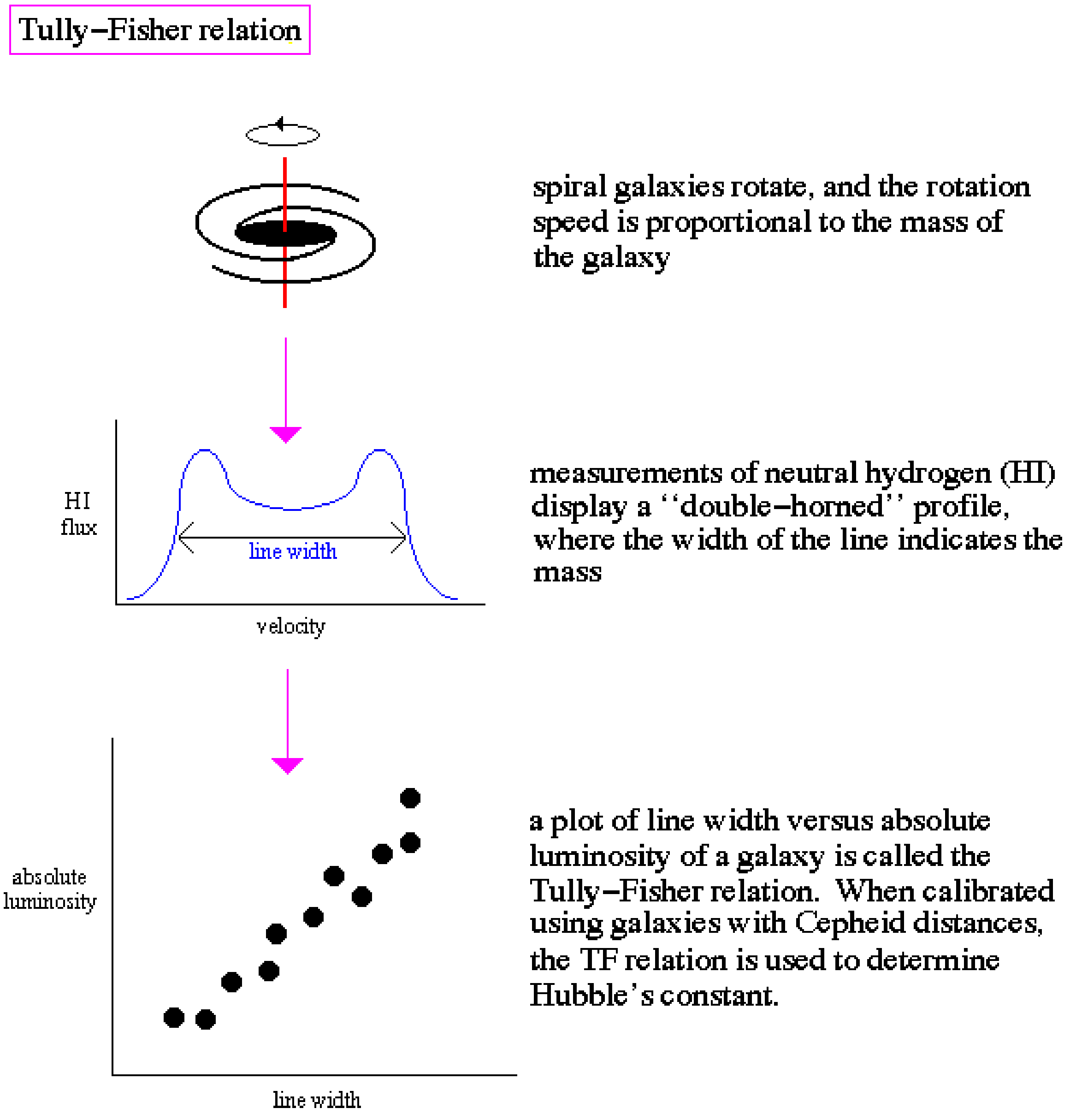



The result is that it is possible to measure the light curve of Cepheids in other galaxies and determine their distances.

Tertiary Calibrators:

The nearby region of the Universe, known as the Local Group and is located at the edge of what is known as the the Virgo supercluster of galaxies. The use of Cepheid variables is limited to within the volume of space outlined by Virgo system. Thus, the distances to nearby galaxies does not measure the true Hubble flow of the expanding Universe, but rather the gravitational infall into Virgo.

In order to determine Hubble's constant, we must measure the velocity of galaxies much farther away then the Local Group or the Virgo supercluster. But, at these distances we cannot see Cepheid stars, so we determine the total luminosity of the galaxy by the Tully-Fisher method, the last leg of the distance scale ladder.




The Tully-Fisher relation is basically a plot of mass versus luminosity of a galaxy. Its not surprising that luminosity and mass are correlated since stars make up basically most of a galaxy's mass and all of the light. Missing mass would be in the form of gas, dust and dark matter.

The key parameter for this last leg of the distance scale are the calibrating galaxies to the Tully-Fisher relation, i.e. the galaxies where we know both the total luminosity from Cepheid

distances and the total luminosity from the Tully-Fisher relation.

There is currently a strong debate on the value of the Hubble's constant fueled by new data from HST Cepheid studies of nearby galaxies. The community is divided into two schools of thought; 1) the old school which proposes a value for Hubble's constant around 50 to agree with the ages of the oldest stars in our Galaxy, and 2) a newer, and larger school which finds a higher Hubble's constant of 75. This higher value poses a problem for modern cosmology in that the age of the Universe from Hubble's constant is less than the age of the oldest stars as determined by nuclear physics.

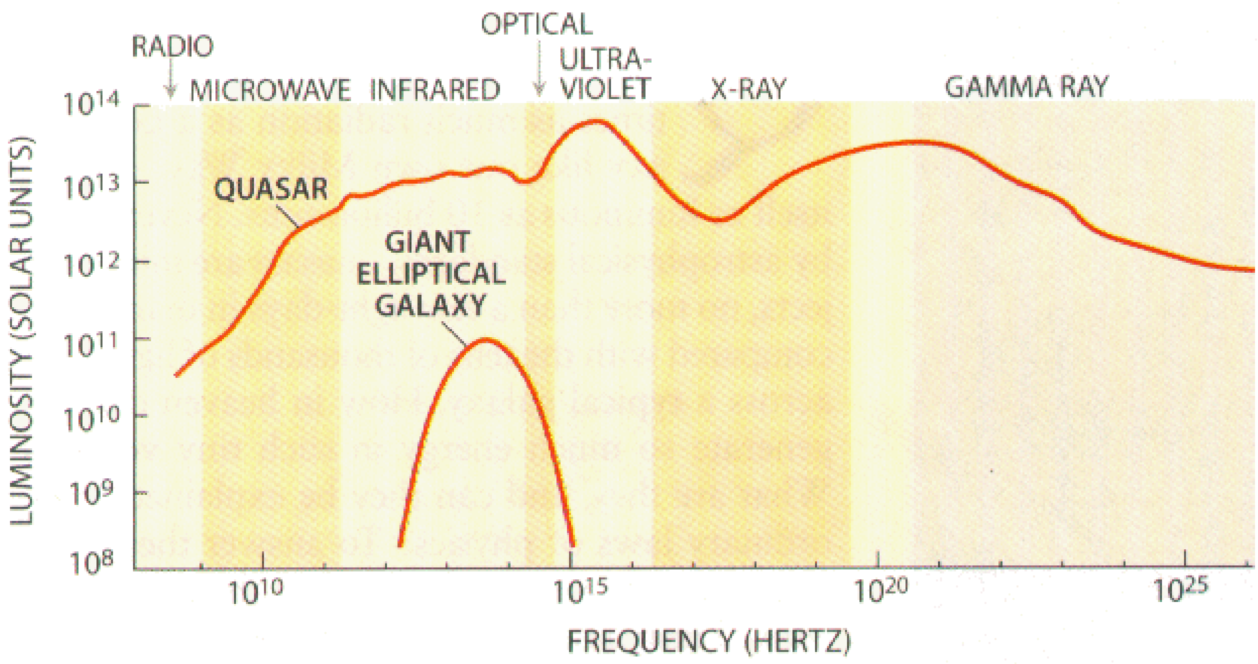
So the dilemma is this, either something is wrong with nuclear physics or something is wrong with our understanding of the geometry of the Universe. One possible solution is the introduction of the cosmological constant, once rejected as unnecessary to cosmology, it has now grown in importance due to the conflict of stellar ages and the age of the Universe.

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Quasars:

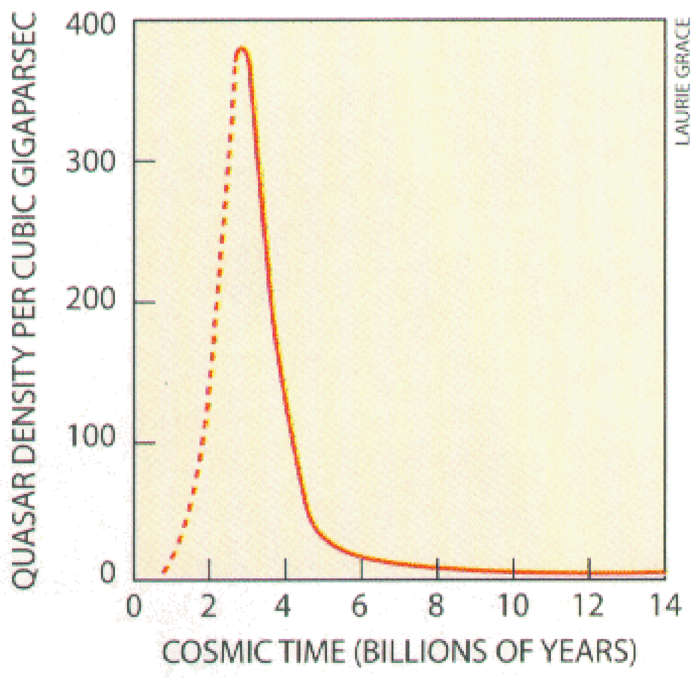
Quasars are the most luminous objects in the Universe. The typical quasar emits 100 to 1000 times the amount of radiation as our own Milky Way galaxy. However, quasars are also variable on the order of a few days, which means that the source of radiation must be contained in a volume of space on a few light-days across. How such amounts of energy can be generated in such small volumes is a challenge to our current physics.

Quasars were originally discovered in the radio region of the spectrum, even though they emit most of their radiation in the high energy x-ray and gamma-ray regions. Optical spectra of the first quasars in the 1960's showed them to be over two billion light-years away, meaning two billion years into the past as well.



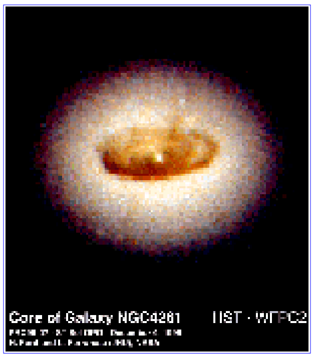

QUASAR SPECTRUM of 3C273—one of the brightest quasars and the first to be discovered—is far broader than the spectrum of a typical giant elliptical galaxy (*left*). In the optical range, the quasar is hundreds of times more luminous. Quasars were most numerous when the universe was two to four billion years old (*right*). Today quasars are 1,000 times less common. Quasars

(right). Today quasars are 1,000 times less common. Quasars were also rare in the very early history of the universe, but the exact numbers are uncertain.




Over a thousand quasars have been discovered, most having redshifts greater than 10 billion light-years away. The number density of quasars drops off very fast, such that they are objects associated with a time when galaxies were young.

The large amount of radio and x-ray emission from quasars gives them similar properties to the class of what are called active galaxies, such as Seyfert galaxies, originally recognized by the American astronomer Carl K. Seyfert from optical spectra. Seyfert galaxies have very bright nuclei with strong emission lines of hydrogen and other common elements, showing velocities of hundreds or thousands of kilometers per second, where the high energy emission is probably due to a Galactic mass black hole at the galaxies core (for example, NGC 4261 shown below). The idea is that quasars are younger, and brighter, versions of Seyfert galaxies.

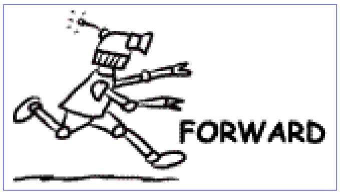



HST imaging showed that quasars are centered in the middle of host galaxies, giving more support to the idea that the quasar phenomenon is associated with Galactic mass black holes in the middle of the host galaxies. Since a majority of the host galaxies are disturbed in appearance, the suspicion is that colliding galaxies cause stars and gas to be tidally pushed into the black hole to fuel the quasar.

This process would explain the occurrence of quasars with redshift. In the far distant past there were no galaxies, so no sites for quasars. In the early phases of galaxy formation, the galaxy

density was high, and there were many collisions producing many quasars. As time passed, the number of collisions decreased as space expanded and the number of quasar also dropped.

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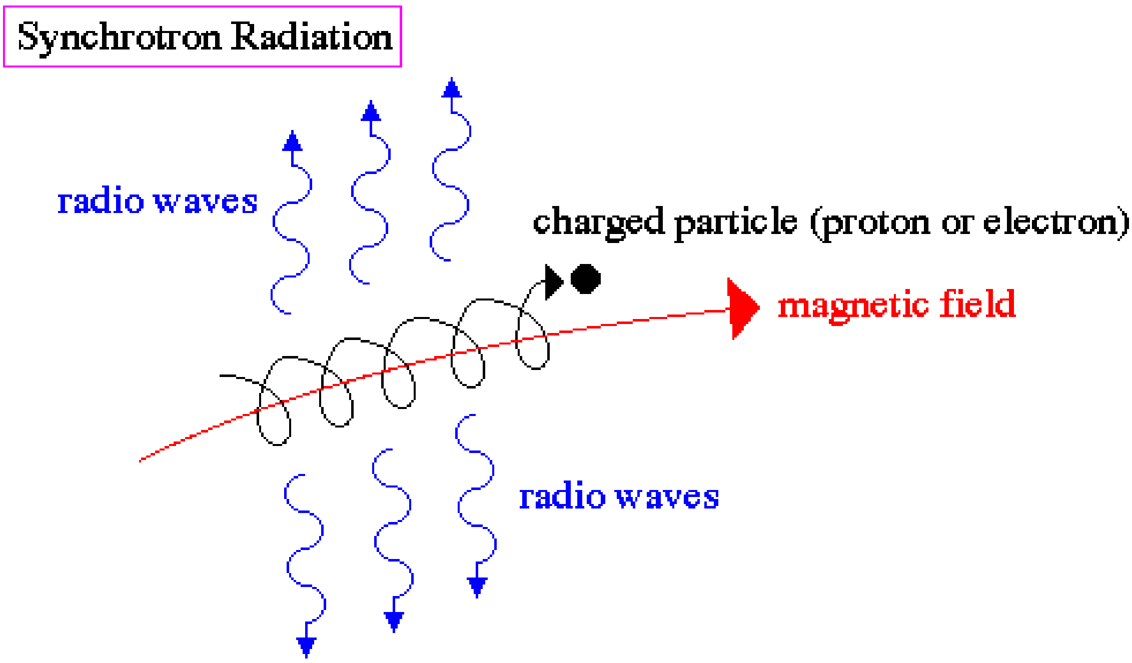

Chapter 25 of Hartman and Impey



Active Galaxies:

Most galaxies are `normal' in that most of their light is generated by stars or heated gas. This energy is primarily radiated away as optical and infrared energy. However, there exists a subclass of galaxies, known as active galaxies, which radiate tremendous amounts of energy in the radio and x-ray regions of the spectrum. These objects often emit hundreds to thousands of times the energy emitted by our Galaxy and, because of this high luminosity, are visible to the edges of the Universe.

Active galaxies usually fall in three types; Seyfert galaxies, radio galaxies and quasars. Radio galaxies often have a double-lobe appearance, and the type of radio emission suggests that the origin is synchrotron radiation.



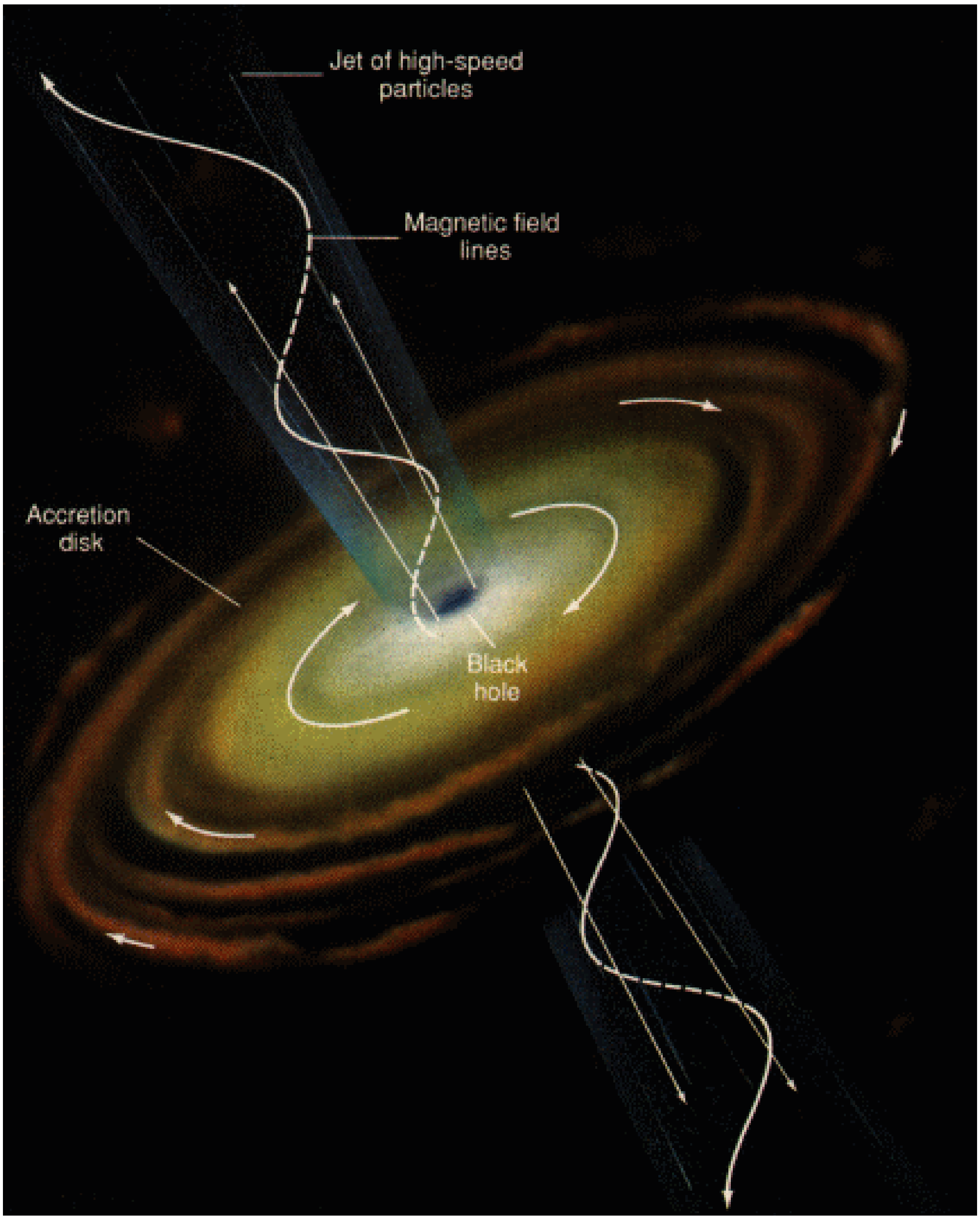

synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

Active galaxies emit large amounts of x-rays and gamma-rays, extremely high energy forms of electromagnetic radiation. Strong magnetic fields (synchrotron radiation in the radiio) plus gamma-rays implies very violent events in the cores of active galaxies.

Although active galaxies different in their appearance, they are related in the mechanism that produces their huge amounts of energy, a Galactic mass black hole at the galaxy's center. The gas flowing towards the center of the galaxy forms a

thick circle of orbiting material called an accretion disk many hundreds of light-years across.

Since the infalling gas retains the direction of orbital motion of the companion, the stream of material forms a rotating disk.




Friction between the gas in neighboring orbits causes the material to spiral inward until it hits the event horizon of the central black hole. As the spiraling gas moves inward, gravitational energy is released as heat into the accretion disk. The release of energy is greatest at the inner edge of the accretion disk where temperatures can reach millions of degrees. It is from this region that the magnetic fields are produced for the synchrotron radiation and the collision between atoms to emit x-rays and gamma-rays.

Our own Galaxy core may harbor a small active nuclei similar to those found in quasars. In fact, all galaxies may have dormant black holes, invisible because there is no accretion. Seyfert, radio galaxies and quasars may simply be normal galaxies

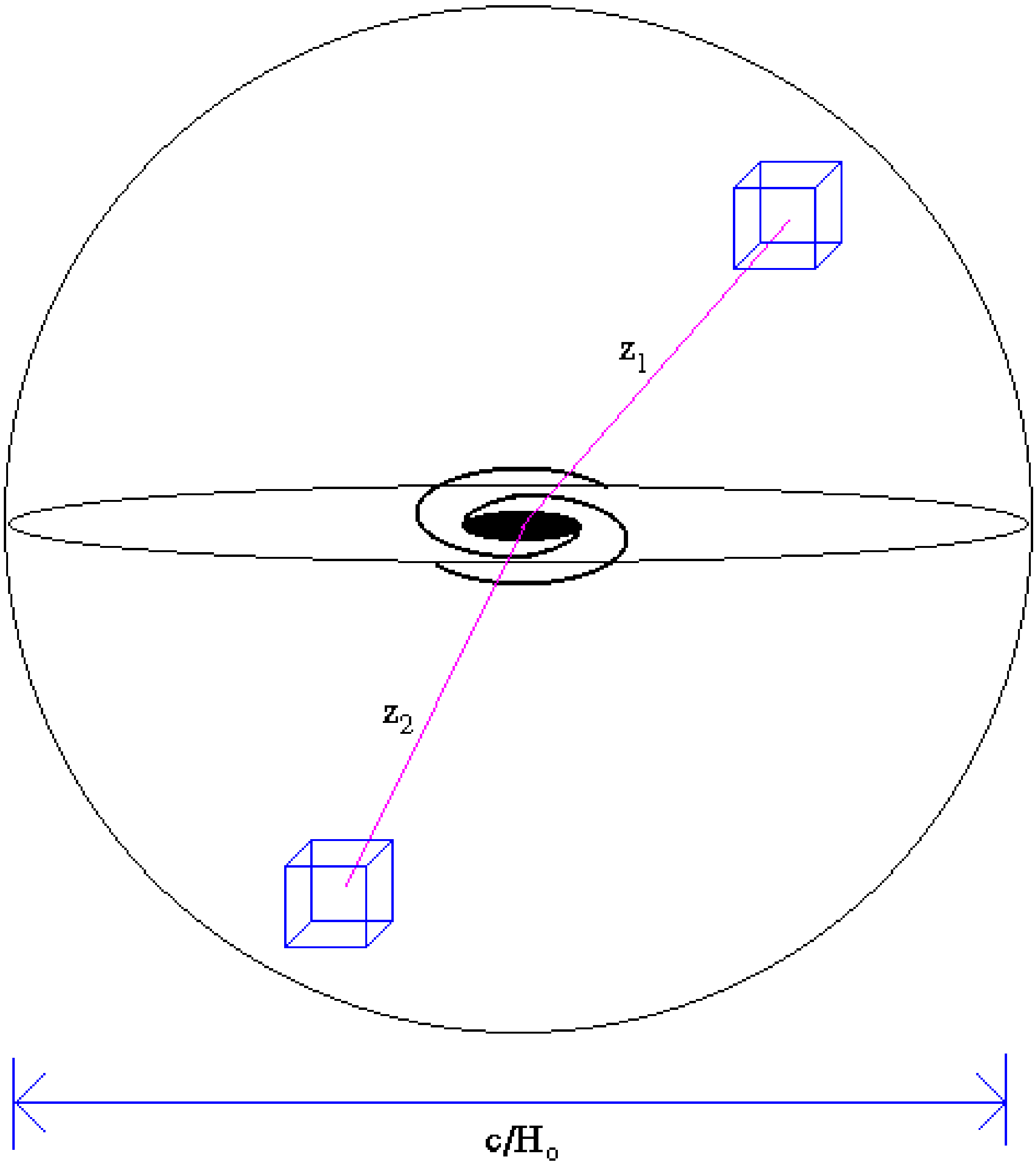
in an active phase.

This hypothesis has been confirmed by HST imaging of distant QSO hosts which show the bright quasar core is in the center of fairly normal looking galaxies.

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Lookback Time:

The large size of the Universe, combined with the finite speed for light, produces the phenomenon known as lookback time. Lookback time means that the farther away an object is from the Earth, the longer it takes for its light to reach us. Thus, we are looking back in time as we look farther away.




The galaxies we see at large distances are younger than the galaxies we see nearby. This allows us to study galaxies as they evolve. Note that we don't see the individuals evolve, but we can compare spirals nearby with spirals far away to see how the typical spiral has changed with time.

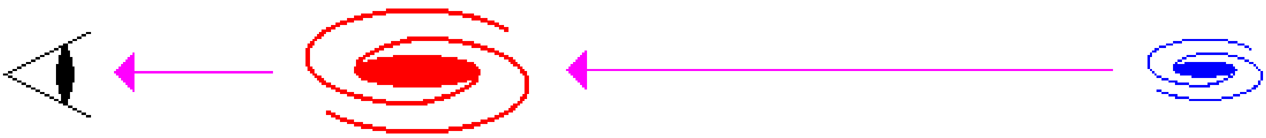
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Galaxy Evolution:

The phenomenon of lookback time allows us to actually observe the evolution of galaxies. We are not seeing the same galaxies as today, but it is possible to trace the behavior of galaxies types with distance/time.

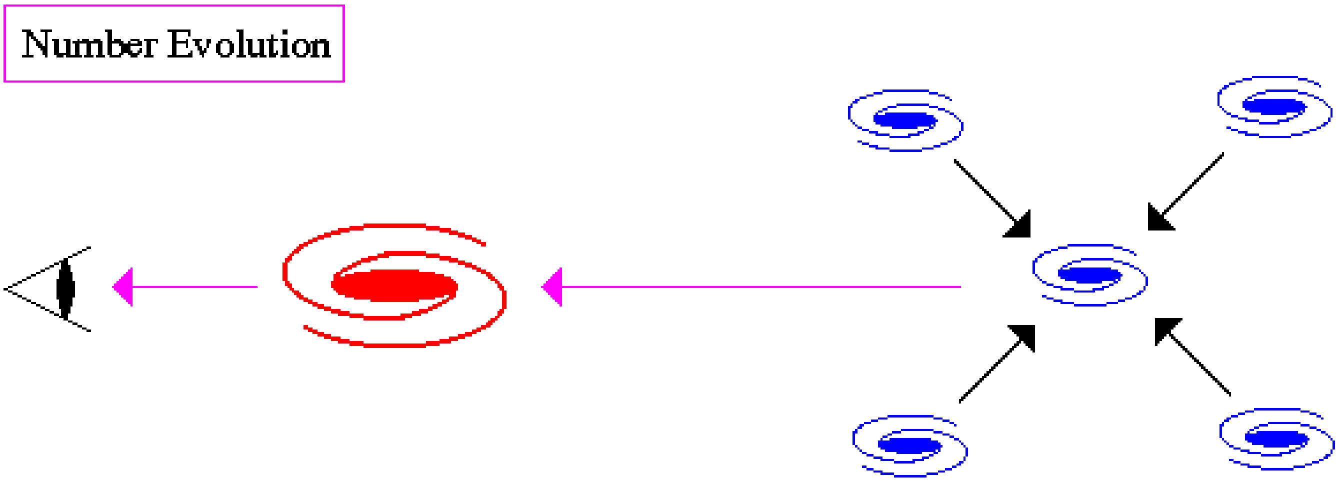
It is known that galaxies form from large clouds of gas in the early Universe. The gas collects under self-gravity and, at some point, the gas fragments into star cluster sized elements where star formation begins. Thus, we have the expectation that distant galaxies (i.e. younger galaxies) will be undergoing large amounts of star formation and producing hot stars = blue stars. The study of this phenomenon is called color evolution.

Color Evolution



distant galaxies are bluer since we are looking back in time, and are seeing them at a younger age, younger stars = hotter stars = bluer stars

Computer simulations also indicate that the epoch right after galaxy formation is a time filled with many encounters/collisions between young galaxies. Galaxies that pass near each other can be captured in their mutual self-gravity and merge into a new galaxy. Note that this is unlike cars, which after collisions are not new types of cars, because galaxies are composed of many individual stars, not solid pieces of matter. The evolution of galaxies by mergers and collisions is called number evolution.

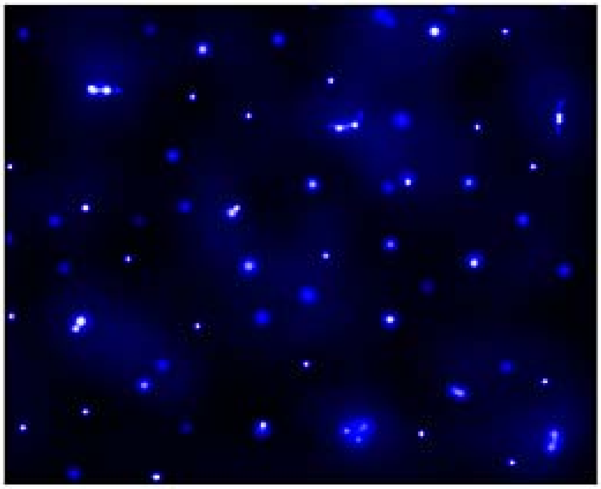



small galaxies merger at early epochs to form present–day galaxies. More galaxies are seen as we look back into the past.

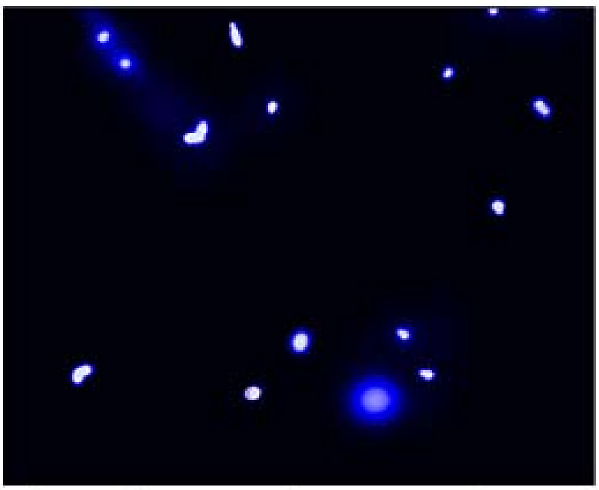
Thus, our picture of galaxy evolution, incorporating both these principles, looks like the following:



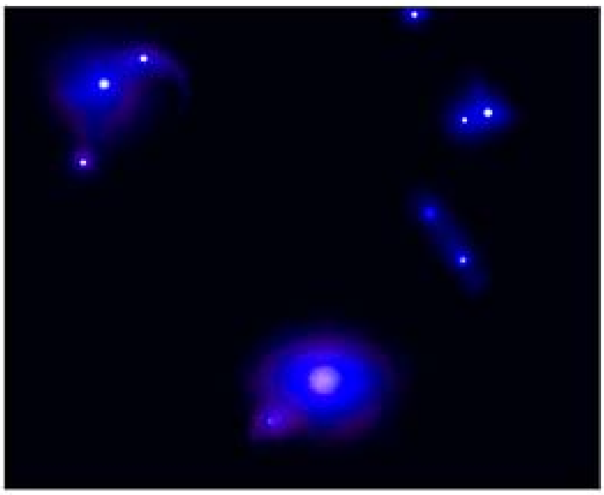
After 0 - 0.5 billion years -- starting out with a very smooth distribution of matter directly after the Big-Bang, gravity of the more massive clumps of stars starts to attract more matter.



After 0.5 - 1 billion years -- larger clumps grow from merging of smaller ones.



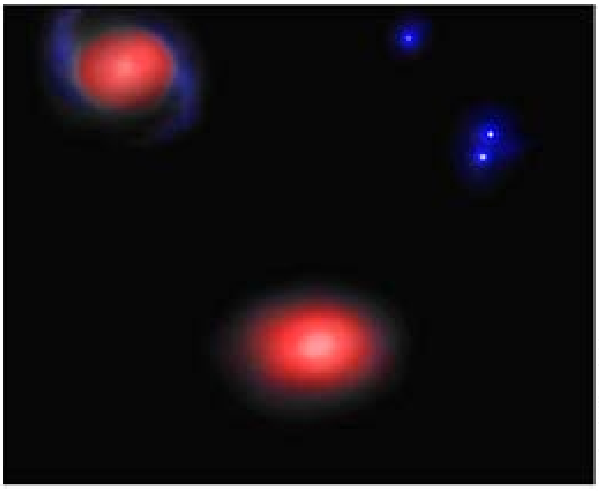
After 1 - 2 billions years -- after growing to a fraction



After 2-4 billion years -- larger irregular looking

of the size of our own Galaxy, the clumps are large enough for Hubble Space Telescope to see them.

objects form through collisions and mergers between these sub-galactic sized clumps.

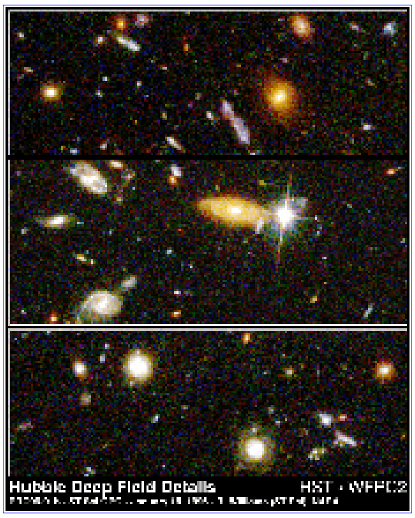


After 4-13 billion years -- galaxies as we see them today form, and take their final shapes. The elliptical and the spiral galaxies with old red stellar populations in their centers form first, and the spiral galaxy disks form later from infalling surrounding gas.

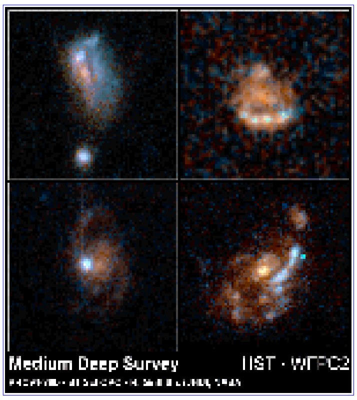
Credit: Sam Pascarelle (Arizona State University)

Some types of galaxies are still forming stars at the present epoch (e.g. spiral and irregular galaxies). However, the past was marked by a much higher rate of star formation than the present-day average rate because there was more gas clouds in the past. Galaxies, themselves, were built in the past from high, initial rates of star formation.

The time of quasars is also during the time of first star formation in galaxies, so the two phenomenon are related, the past was a time of rapid change and violent activity in galaxies.




Space observations called the Hubble Deep Field produced images of faint galaxies and distant galaxies at high redshift which confirmed, quantitatively, our estimates of the style and amount of star formation. Nature lends a hand by providing images of distant galaxies by gravitational lensing, as seen in this HST image of CL0024.

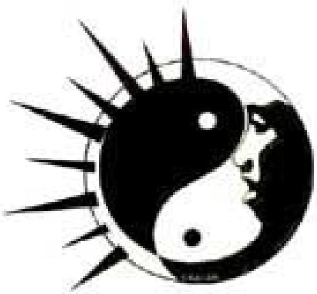



Interestingly enough, it is often easier to simulate the evolution of galaxies in a computer, then use the simulations to solve for various cosmological constants, such as Hubble's constant or the geometry of the Universe. The field of extragalactic studies is just such a process of iteration on the fundamental constants of the Universe and the behavior of galaxies with time (i.e. galaxy evolution).

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Creation Event:

The debate about the origin of the Universe presupposes that there was an origin. Instead of a beginning, the Universe may be experiencing an endless number of cycles. Ancient Chinese believed that all events formed a periodic pattern driven by two basic forces, Yin and Yang.



The Hindu cosmological system consisted of cycles within cycles of immense duration (one lifecycle of Brahma is 311 trillion years). Cyclicity cosmologies, and their associated fatalism, is also found in Babylonian, Egyptian and Mayan cultures.

Judeo-Christian tradition was unique in its belief that God created the Universe at some specfic moment in the past, and that events form an unfolding unidirectional sequence. Key to this philosophy is that the Creator is entirely separate from and independent of His creation. God brings order to a primordal chaos.



Belief that a divine being starts the Universe then `sits back' and watchs events unfold, taking no direct part in affairs, is known as deism. Here God is considered a cosmic engineer. In contrast, theism is the belief in a God who is creator of the Universe and who also remains directly involved in the day-to-day running of the world, especially the affairs of human beings. God maintains a personal and guiding role. In both deism and theism, God is regarded as wholly other than, and beyond, the physical Universe. In pantheism, no such separation is made between God and the physical Universe. God is identified with Nature itself: everything is a part of God and God is in everything.

A Creation event implies that everything came from nothing (creation ex nihilo) since if there were something before Creation, than an earlier Creation is needed to explain that something. God existed before Creation, and the definition is not limited to work with pre-existing matter or pre-existing physical laws either. In fact, the most obvious distinction between the Creator and the created Universe is that the Creator is eternal and the created Universe had a beginning.

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Hot Big Bang:

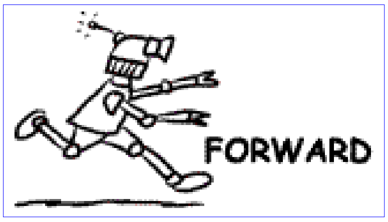
The discovery of an expanding Universe implies the obvious, that the Universe must have had an initial starting point, an alpha point or Creation. In other words, there existed a point in the past when the radius of the Universe was zero. Since all the matter in the Universe must have been condensed in a small region, along with all its energy, this moment of Creation is referred to as the Big Bang.

A common question that is asked when considering a Creation point in time is ``What is before the Big Bang?''. This type is question is meaningless or without context since time was created with the Big Bang. It is similar to asking ``What is north of the North Pole?''. The question itself can not be phrased in a meaningful way.

The Big Bang theory has been supported by numerous observations and, regardless of the details in our final theories of the Universe, remains the core element to our understanding of the past. Note that an alpha point automatically implies two things: 1) the Universe has a finite age (about 15 billion years) and 2) the Universe

has a finite size (its expanding at a finite speed in a finite time).

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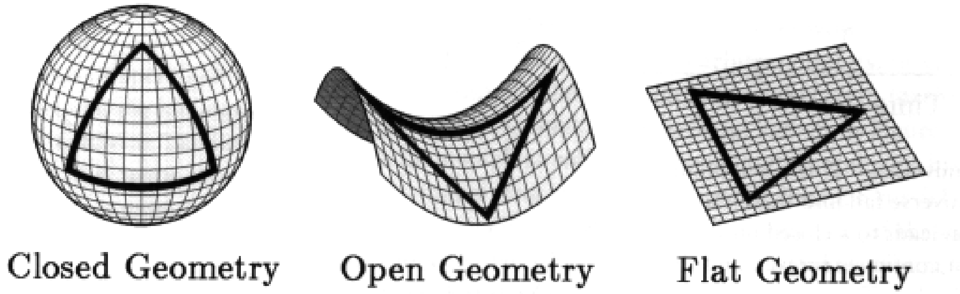





Geometry of the Universe:

Can the Universe be finite in size? If so, what is ``outside" the Universe? The answer to both these questions involves a discussion of the intrinsic geometry of the Universe.

There are basically three possible shapes to the Universe; a flat Universe (Euclidean or zero curvature), a spherical or closed Universe (positive curvature) or a hyperbolic or open Universe (negative curvature). Note that this curvature is similar to spacetime curvature due to stellar masses except that the entire mass of the Universe determines the curvature. So a high mass Universe has positive curvature, a low mass Universe has negative curvature.

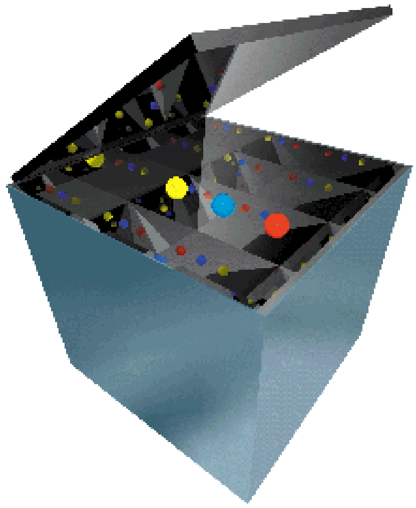



All three geometries are classes of what is called Riemannian geometry, based on three possible states for parallel lines

- never meeting (flat or Euclidean)
- must cross (spherical)
- always divergent (hyperbolic)

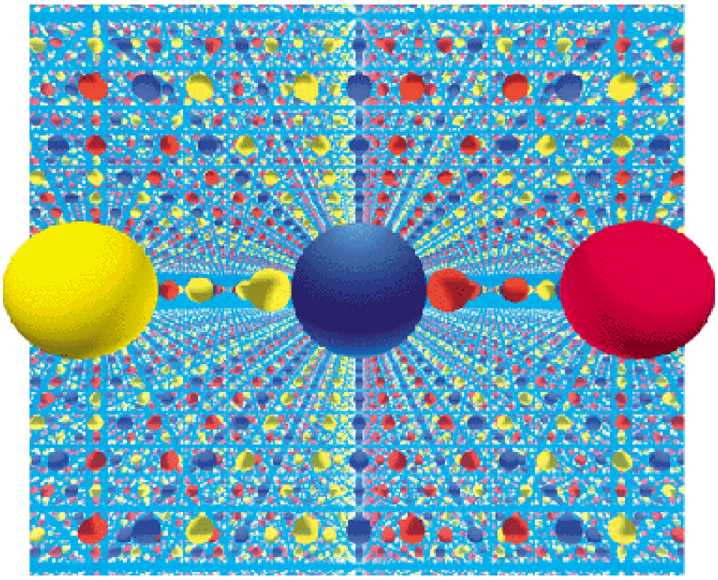
or one can think of triangles where for a flat Universe the angles of a triangle sum to 180 degrees, in a closed Universe the sum must be greater than 180, in an open Universe the sum must be less than 180.

Standard cosmological observations do not say anything about how those volumes fit together to give the universe its overall shape--its topology. The three plausible cosmic geometries are consistent with many different topologies. For example, relativity would describe both a torus (a doughnutlike shape) and a plane with the same equations, even though the torus is finite and the plane is infinite. Determining the topology requires some physical understanding beyond relativity.

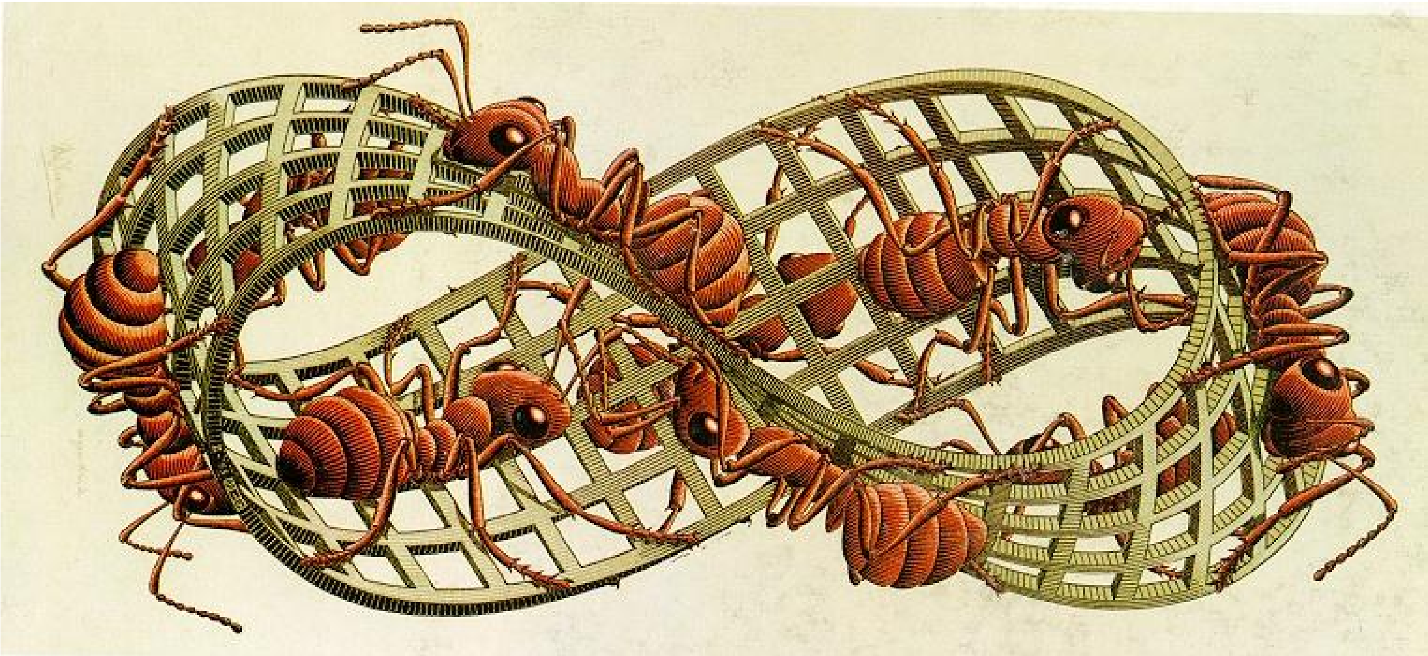


Like a hall of mirrors, the apparently endless universe might be deluding us. The cosmos could, in fact, be finite. The illusion of infinity would come about as light wrapped all the way around space, perhaps more than once--creating multiple images of each galaxy. A mirror box evokes a finite cosmos that looks

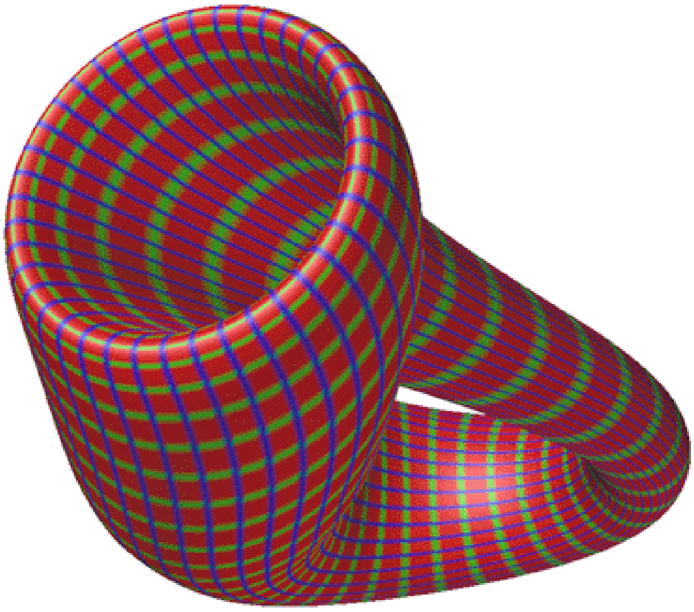
endless. The box contains only three balls, yet the mirrors that line its walls produce an infinite number of images. Of course, in the real universe there is no boundary from which light can reflect. Instead a multiplicity of images could arise as light rays wrap around the universe over and over again. From the pattern of repeated images, one could deduce the universe's true size and shape.



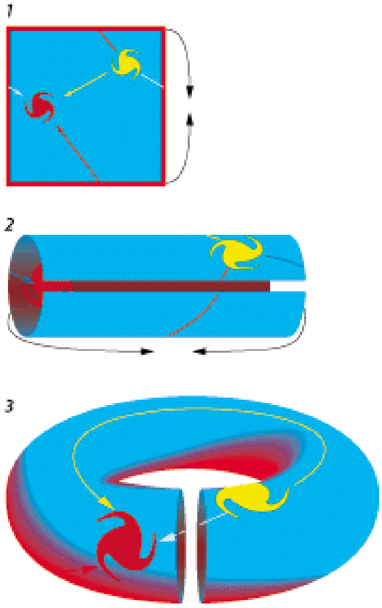
Topology shows that a flat piece of spacetime can be folded into a torus when the edges touch. In a similar manner, a flat strip of paper can be twisted to form a Moebius Strip.



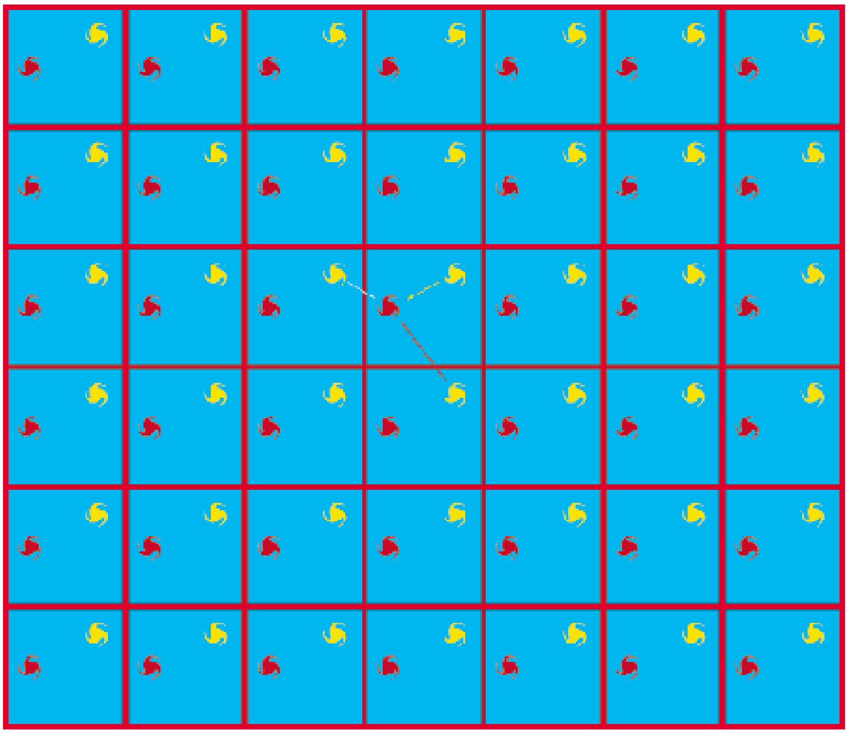
The 3D version of a moebius strip is a Klein Bottle, where spacetime is distorted so there is no inside or outside, only one surface.



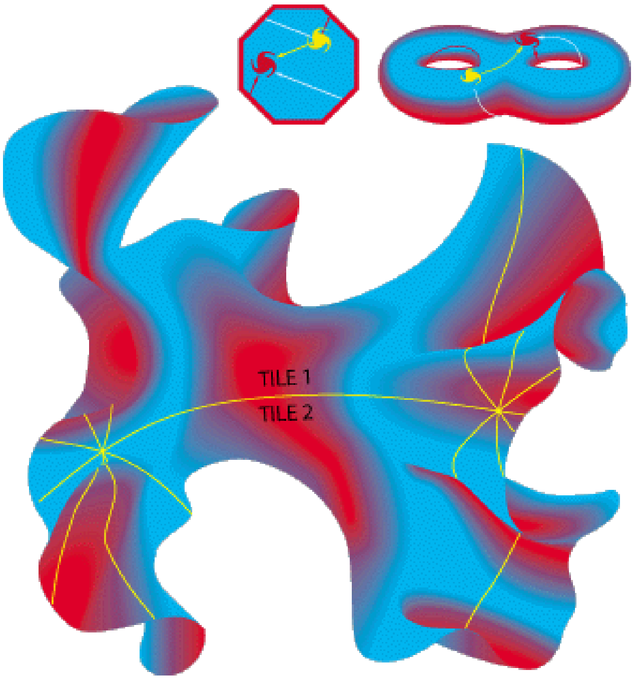
The usual assumption is that the universe is, like a plane, "simply connected," which means there is only one direct path for light to travel from a source to an observer. A simply connected Euclidean or hyperbolic universe would indeed be infinite. But the universe might instead be "multiply connected," like a torus, in which case there are many different such paths. An observer would see multiple images of each galaxy and could easily misinterpret them as distinct galaxies in an endless space, much as a visitor to a mirrored room has the illusion of seeing a huge crowd.




One possible finite geometry is donutspace or more properly known as the Euclidean 2-torus, is a flat square whose opposite sides are connected. Anything crossing one edge reenters from the opposite edge (like a video game see 1 above). Although this surface cannot exist within our three-dimensional space, a distorted version can be built by taping together top and bottom (see 2 above) and scrunching the resulting cylinder into a ring (see 3 above). For observers in the pictured red galaxy, space seems infinite because their line of sight never ends (below). Light from the yellow galaxy can reach them along several different paths, so they see more than one image of it. A Euclidean 3-torus is built from a cube rather than a square.



A finite hyperbolic space is formed by an octagon whose opposite sides are connected, so that anything crossing one edge reenters from the opposite edge (top left). Topologically, the octagonal space is equivalent to a two-holed pretzel (top right). Observers who lived on the surface would see an infinite octagonal grid of galaxies. Such a grid can be drawn only on a hyperbolic manifold--a strange floppy surface where every point has the geometry of a saddle (bottom).



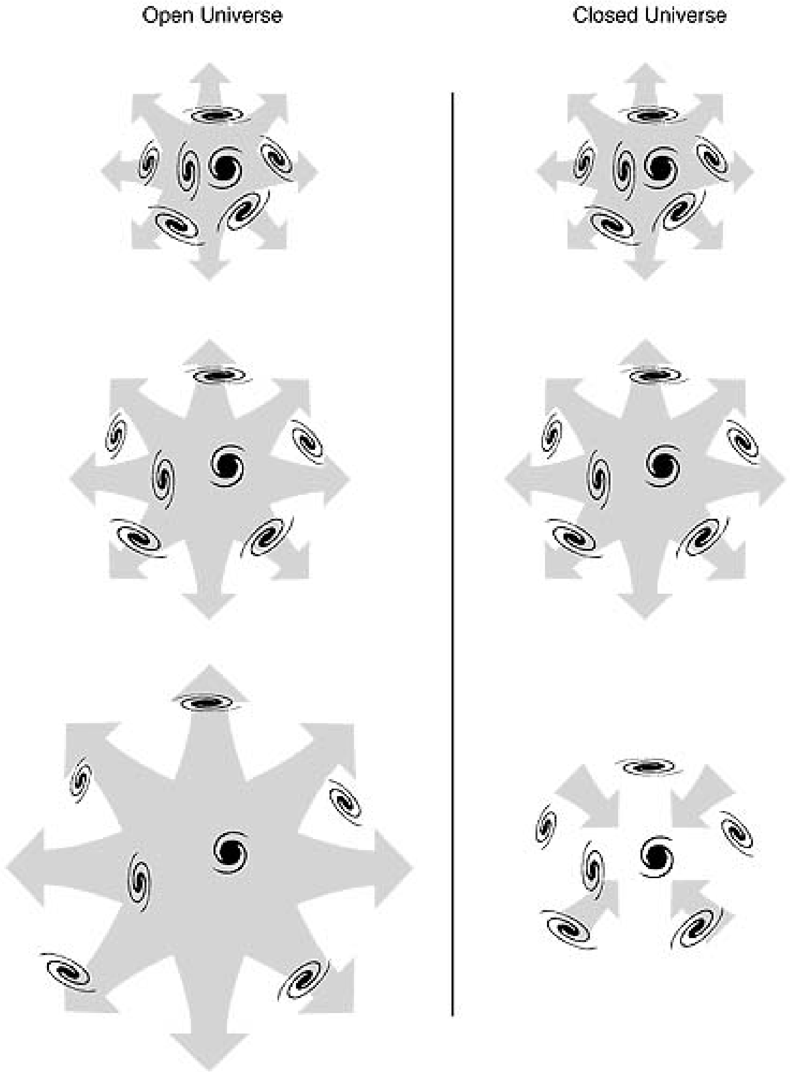

Its important to remember that the above images are 2D shadows of 4D space, it is impossible to draw the geometry of the Universe on a piece of paper (although we can come close with a hypercube), it can only be described by mathematics. All possible Universes are finite since there is only a finite age and, therefore, a limiting horizon. The geometry may be flat or open, and therefore infinite in possible size (it continues to grow forever), but the amount of mass and time in our Universe is finite.

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Density of the Universe:

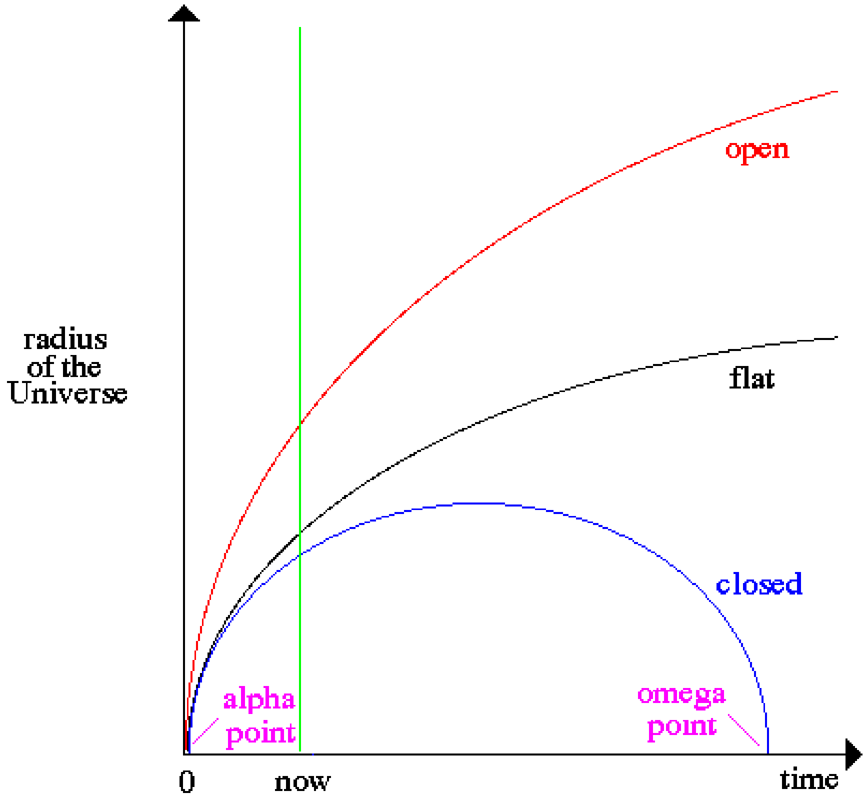
The description of the various geometries of the Universe (open, closed, flat) also relate to their futures.

There are two possible futures for our Universe, continual expansion (open and flat), turn-around and collapse (closed). Note that flat is the specific case of expansion to zero velocity.




An open universe expands forever because it does not contain enough mass, and so does not have enough gravity to slow the expansion of space. A closed universe contains enough mass to halt the expansion, and eventually collapses A universe with a "critical density" of matter in space is exactly balanced between these two alternatives, and expands at an ever-slowing rate.

The key factor that determines which history is correct is the amount of mass/gravity for the Universe as a whole. If there is sufficient mass, then the expansion of the Universe will be slowed to the point of stopping, then retraction to collapse. If there is not a sufficient amount of mass, then the Universe will expand forever without stopping. The flat Universe is one where there is exactly the balance of mass to slow the expansion to zero, but not for collapse.




The parameter that is used to measure the mass of the Universe is the critical density, Omega. Omega is usually expressed as the ratio of the mean density observed to that of the density in a flat Universe.

**$\Omega$, the cosmic density parameter**

the fate of the expanison of the Universe is determined by the amount of mass in the Universe, or the mean density of matter, $\rho$

a flat Universe is given a critical density, $\rho_c$

$\Omega$ is defined as the ratio of the observed density, $\rho_c$ to the critical density, $\rho$ such that

$$\Omega = \frac{\rho}{\rho_c}$$

a closed Universe has $\Omega > 1$

an open Universe has $\Omega < 1$

our current observations of the Universe indicate that $\Omega$ is between 0.1 and 0.3, but there is strong theoretical reasons to believe $\Omega$ is 1

Given all the range of values for the mean density of the Universe, it is strangely close to the density of a flat Universe. And our theories of the early Universe (see inflation) strongly suggest the value of Omega should be exactly equal to one. If so our measurements of the density by galaxy counts or dynamics are grossly in error and remains one of the key problems for modern astrophysics.

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Cosmological Constants:

The size, age and fate of the Universe are determined by two constants:

Fundamental Cosmological Constants

The two most fundamental cosmological constants are Hubble's contant ($H_o$) which measures the expansion rate of the Universe and the density measure $\Omega_o$, where the ''o'' indicates these values today.

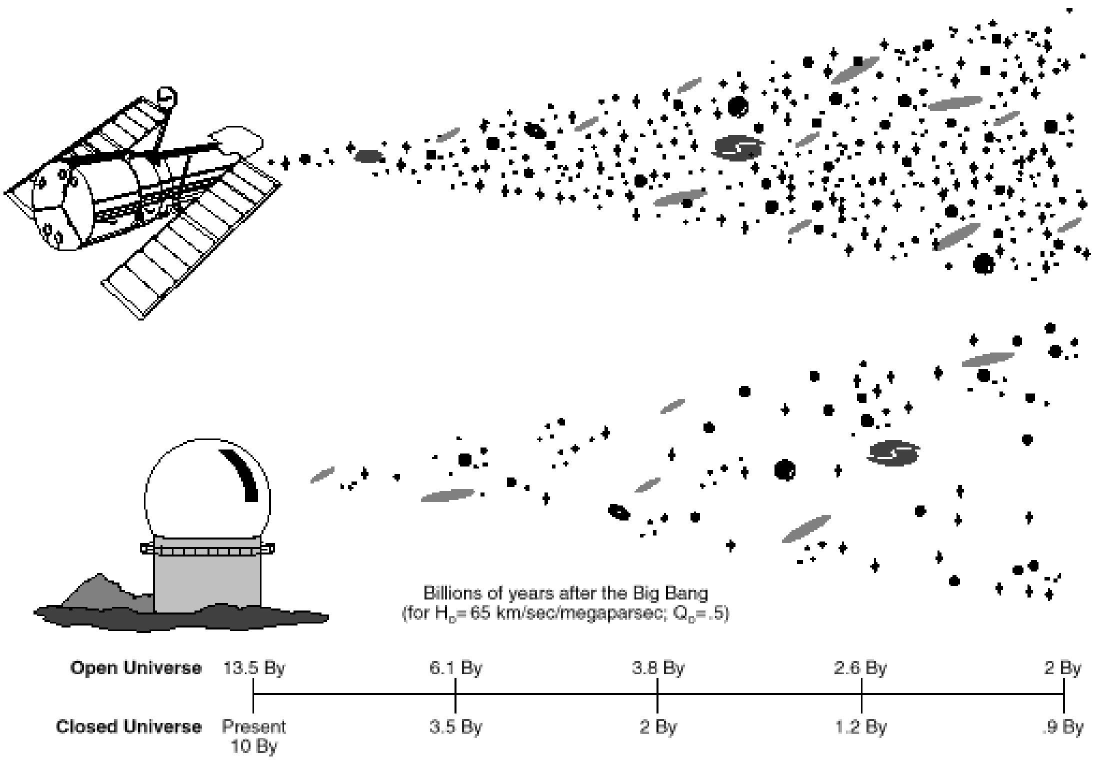
$H_o$ sets the scale and the age of the Universe, in the sense that the distance to galaxies is determined from their recessional velocity divided by $H_o$ and the age of the Universe is simply the size of the Universe divided by the expansion rate or $1/H_o$

The density measure, $\Omega_o$ determines the fate of the Universe (open, closed or flat)

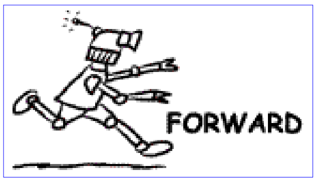
$H_o$ is measured by determining the distance scale of galaxies

$\Omega_o$ is measured by estimating the local mass density from gravity forces between galaxies and clusters of galaxies

The measurement of these constants consumes major amounts of telescope time over all wavelengths. Both constants remain uncertain to about 30%; however, within this decade we can expect to measure highly accurate values for both due to the Hubble Space Telescope and the Keck twins.




The Hubble Deep Field uncovered much fainter objects in the universe (down to nearly 30th magnitude) than seen previously from ground-based telescopes. Some of the dim objects along Hubble's line-of sight may be intrinsically faint, foreground galaxies. Others, however, are dim because they are extremely distant. Some of the faintest galaxies in the survey existed when the universe was a fraction of it's present age.

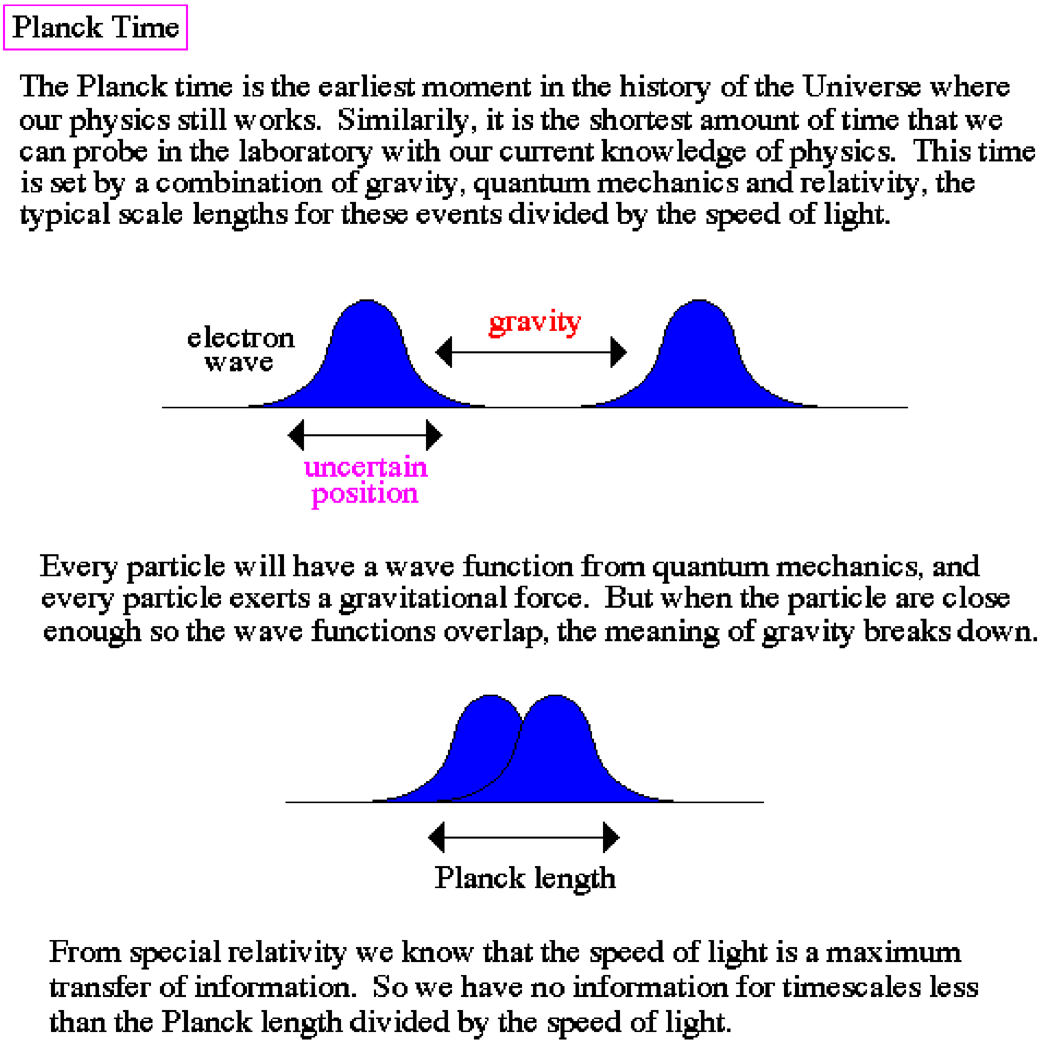

FORWARD


BACKWARD

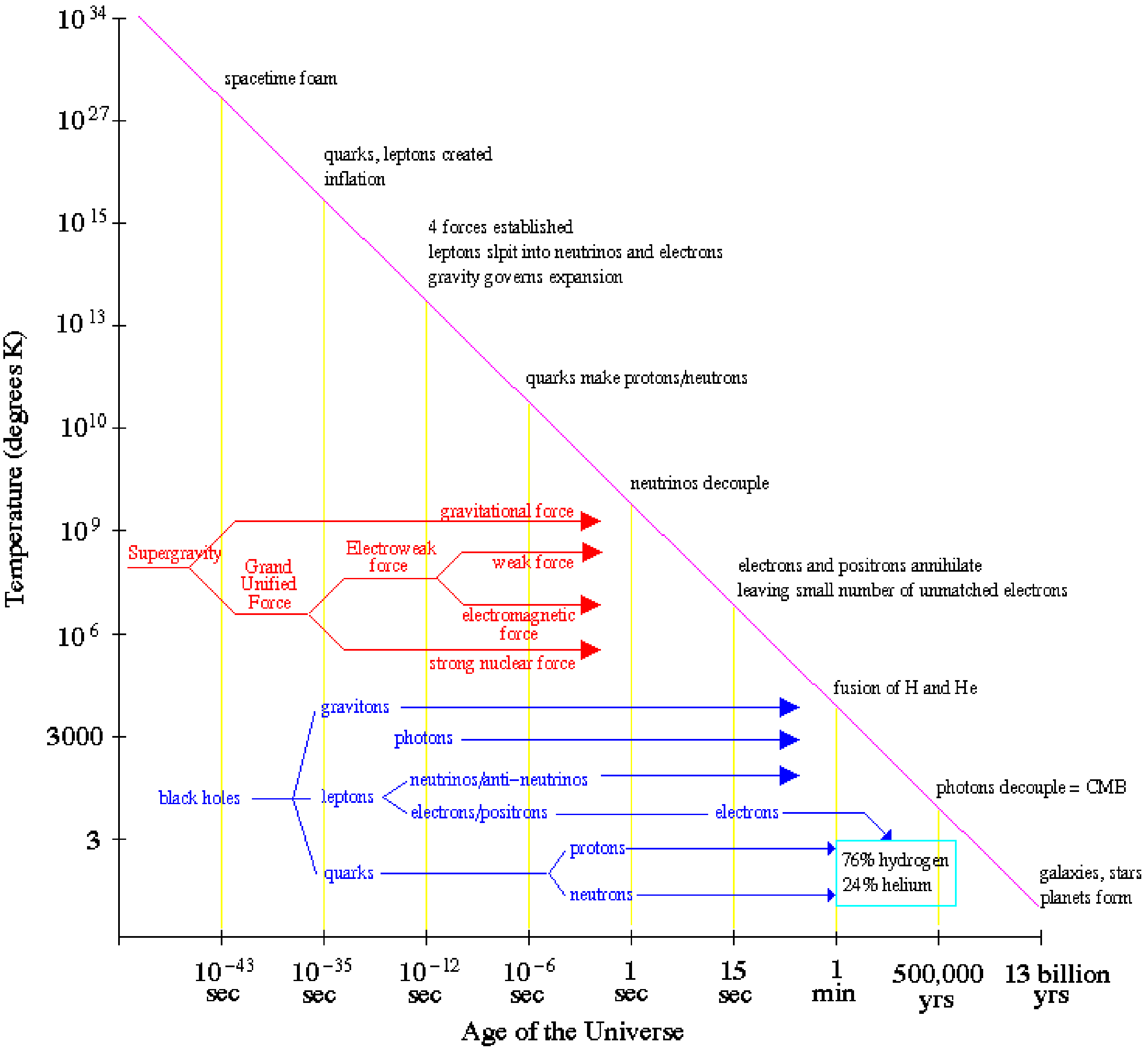
Birth of the Universe :

Physics of the early Universe is at the boundary of astronomy and philosophy since we do not currently have a complete theory that unifies all the fundamental forces of Nature at the moment of Creation. In addition, there is no possibility of linking observation or experimentation of early Universe physics to our theories (i.e. its not possible to `build' another Universe). Our theories are rejected or accepted based on simplicity and aesthetic grounds, plus there power of prediction to later times, rather than an appeal to empirical results. This is a very difference way of doing science from previous centuries of research.

Our physics can explain most of the evolution of the Universe after the Planck time (approximately $10^{-43}$ seconds after the Big Bang).




However, events before this time are undefined in our current science and, in particular, we have no solid understanding of the origin of the Universe (i.e. what started or `caused' the Big Bang). At best, we can describe our efforts to date as probing around the `edges' of our understanding in order to define what we don't understand, much like a blind person would explore the edge of a deep hole, learning its diameter without knowing its depth.

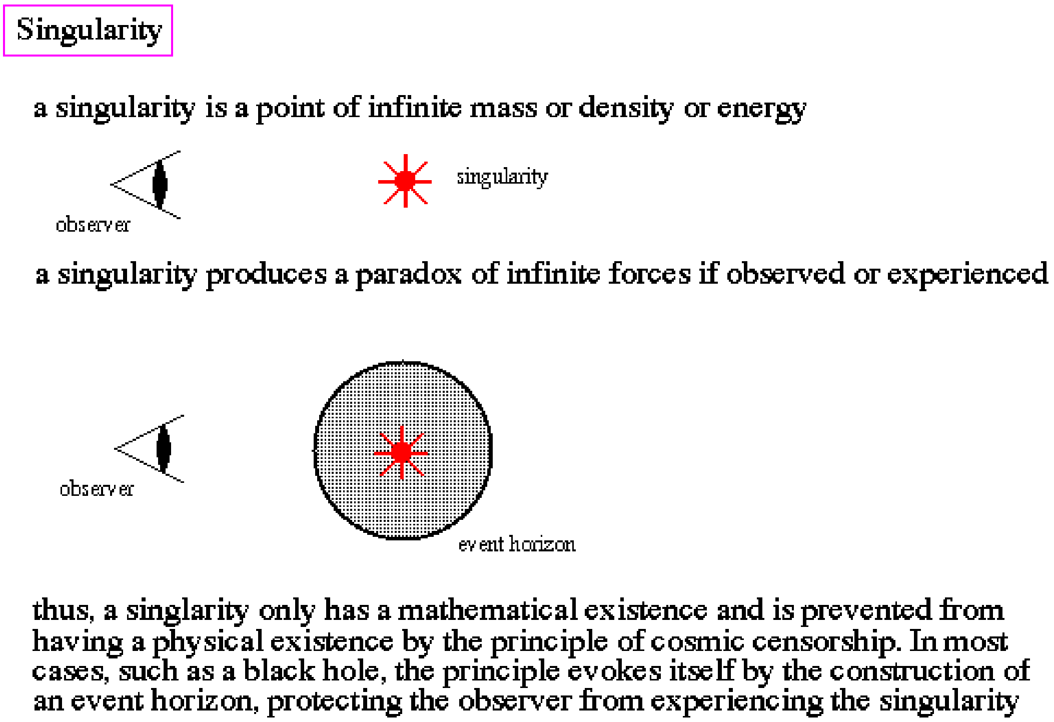



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Cosmic Singularity :

One thing is clear in our framing of questions such as `How did the Universe get started?' is that the Universe was self-creating. This is not a statement on a `cause' behind the origin of the Universe, nor is it a statement on a lack of purpose or destiny. It is simply a statement that the Universe was emergent, that the actual of the Universe probably derived from a indeterminate sea of potentiality that we call the quantum vacuum, whose properties may always remain beyond our current understanding.

Extrapolation from the present to the moment of Creation implies an origin of infinite density and infinite temperature (all the Universe's mass and energy pushed to a point of zero volume). Such a point is called the cosmic singularity.




Infinites are unacceptable as physical descriptions, but our hypothetical observers back at the beginning of time are protected by the principle of cosmic censorship. What this means is that singularities exists only mathematically and not as a physical reality that we can observe or measure. Nature's solution to this problem are things like the event horizon around black holes. Barriers built by relativity to prevent observation of a singularity.

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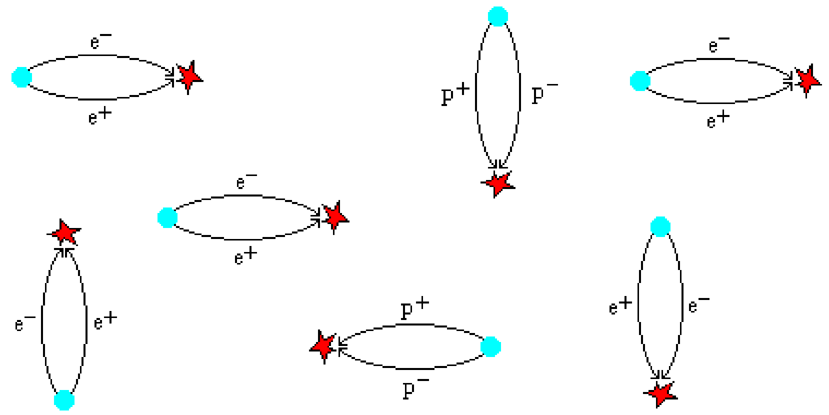
Quantum Vacuum:

The cosmic singularity, that was the Universe at the beginning of time, is shielded by the lack of any physical observers. But the next level of inquiry is what is the origin of the emergent properties of the Universe, the properties that become the mass of the Universe, its age, its physical constants, etc. The answer appears to be that these properties have their origin as the fluctuations of the quantum vacuum.

The properties of the Universe come from `nothing', where nothing is the quantum vacuum, which is a very different kind of nothing. If we examine a piece of `empty' space we see it is not truly empty, it is filled with spacetime, for example. Spacetime has curvature and structure, and obeys the laws of quantum physics. Thus, it is filled with potential particles, pairs of virtual matter and anti-matter units, and potential properties at the quantum level.

Quantum Vacuum

the quantum vacuum cannot be perceived or measured directly since it appears to be empty, in fact it is filled with potentiality




within the quantum vacuum, pairs of virtual matter and anti-matter particles are continually created and destroyed, borrowing their mass/energy by the uncertainity principle. They do not exist as observable entities, but their existence is exerted on other particles as a subtle pressure (called the Casimir effect)

The creation of virtual pairs of particles does not violate the law of conservation of mass/energy because they only exist for times much less than the Planck time. There is a temporary violation of the law of conservation of mass/energy, but this violation occurs within the timescale of the uncertainty principle and, thus, has no impact on macroscopic laws.

The quantum vacuum is the ground state of energy for the Universe, the lowest possible level. Attempts to perceive the vacuum directly only lead to a confrontation with a void, a background that appears to be empty. But, in fact, the quantum vacuum is the source of all potentiality. For example, quantum entities have both wave and particle characteristics. It is the quantum vacuum that such characteristics emerge from, particles `stand-out' from the vacuum, waves `undulate' on the underlying vacuum, and leave their signature on objects in the real Universe.

In this sense, the Universe is not filled by the quantum vacuum, rather it is `written on' it, the substratum of all existence.

With respect to the origin of the Universe, the quantum vacuum must have been the source of the laws of Nature and the properties that we observe today. How those laws and properties emerge is unknown at this time.

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Quantum Fluctuations :

The fact that the Universe exists should not be a surprise in the context of what we know about quantum physics. The uncertainty and unpredictability of the quantum world is manifested in the fact that whatever *can* happen, *does* happen (this is often called the principle of totalitarianism, that if a quantum mechanical process is not strictly forbidden, then it must occur).

For example, radioactive decay occurs when two protons and two neutrons (an alpha particle) leap out of an atomic nuclei. Since the positions of the protons and neutrons is governed by the wave function, there is a small, but finite, probability that all four will quantum tunnel outside the nucleus, and therefore escape. The probability of this happening is small, but given enough time (tens of years) it *will* happen.

The same principles were probably in effect at the time of the Big Bang (although we can not test

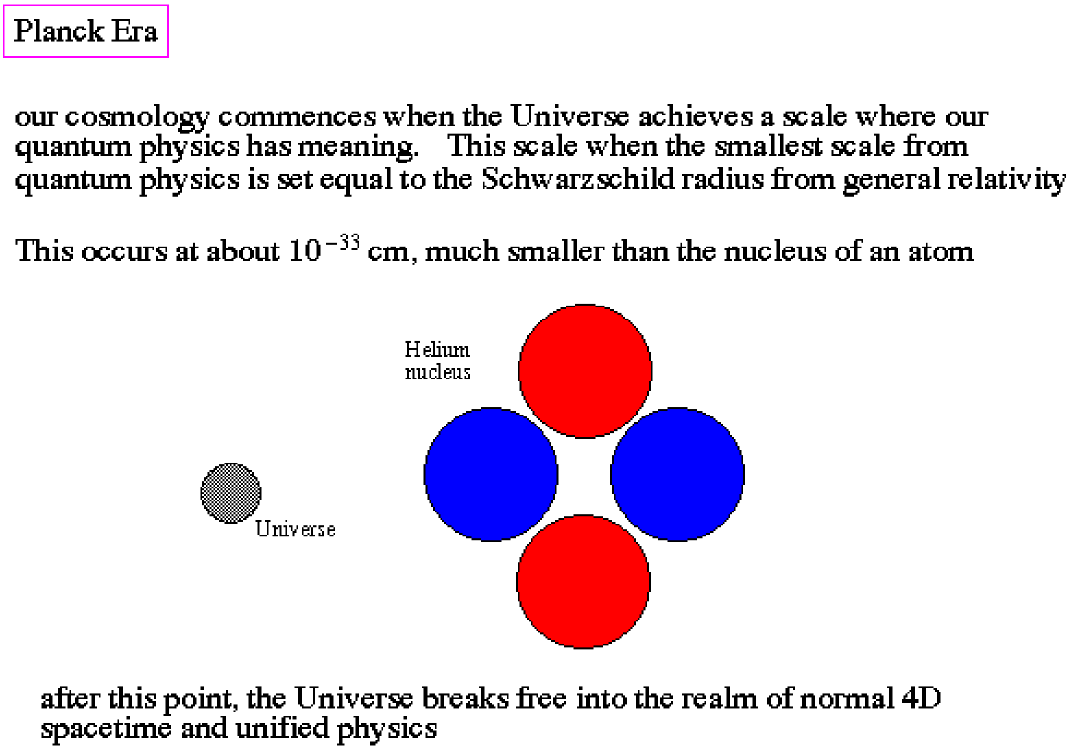
this hypothesis within our current framework of physics). But as such, the fluctuations in the quantum vacuum effectively guarantee that the Universe would come into existence.

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Planck Era :

The earliest moments of Creation are where our modern physics breakdown, where `breakdown' means that our theories and laws have no ability to describe or predict the behavior of the early Universe. Our everyday notions of space and time cease to be valid.

Although we have little knowledge of the Universe before the Planck time, only speculation, we can calculate when this era ends and when our physics begins. The hot Big Bang model, together with the ideas of modern particle physics, provides a sound framework for sensible speculation back to the Planck era. This occurs when the Universe is at the Planck scale in its expansion.




Remember, there is no `outside' to the Universe. So one can only measure the size of the Universe much like you measure the radius of the Earth. You don't dig a hole in the Earth and lower a tape measure, you measure the circumference (take an airplane ride) of the Earth and divide by 2 pi (i.e. C = 2 x pi x radius).

The Universe expands from the moment of the Big Bang, but until the Universe reaches the size of the Planck scale, there is no time or space. Time remains undefined, space is compactified. String theory maintains that the Universe had 10 dimensions during the Planck era, which collapses into 4 at the end of the Planck era (think of those extra 6 dimensions as being very, very small hyperspheres inbetween the space between elementary particles, 4 big dimensions and 6 little tiny ones).

During the Planck era, the Universe can be best described as a quantum foam of 10 dimensions containing Planck length sized black holes continuously being created and annihilated with no cause or effect. In other words, try not to think about this era in normal terms.

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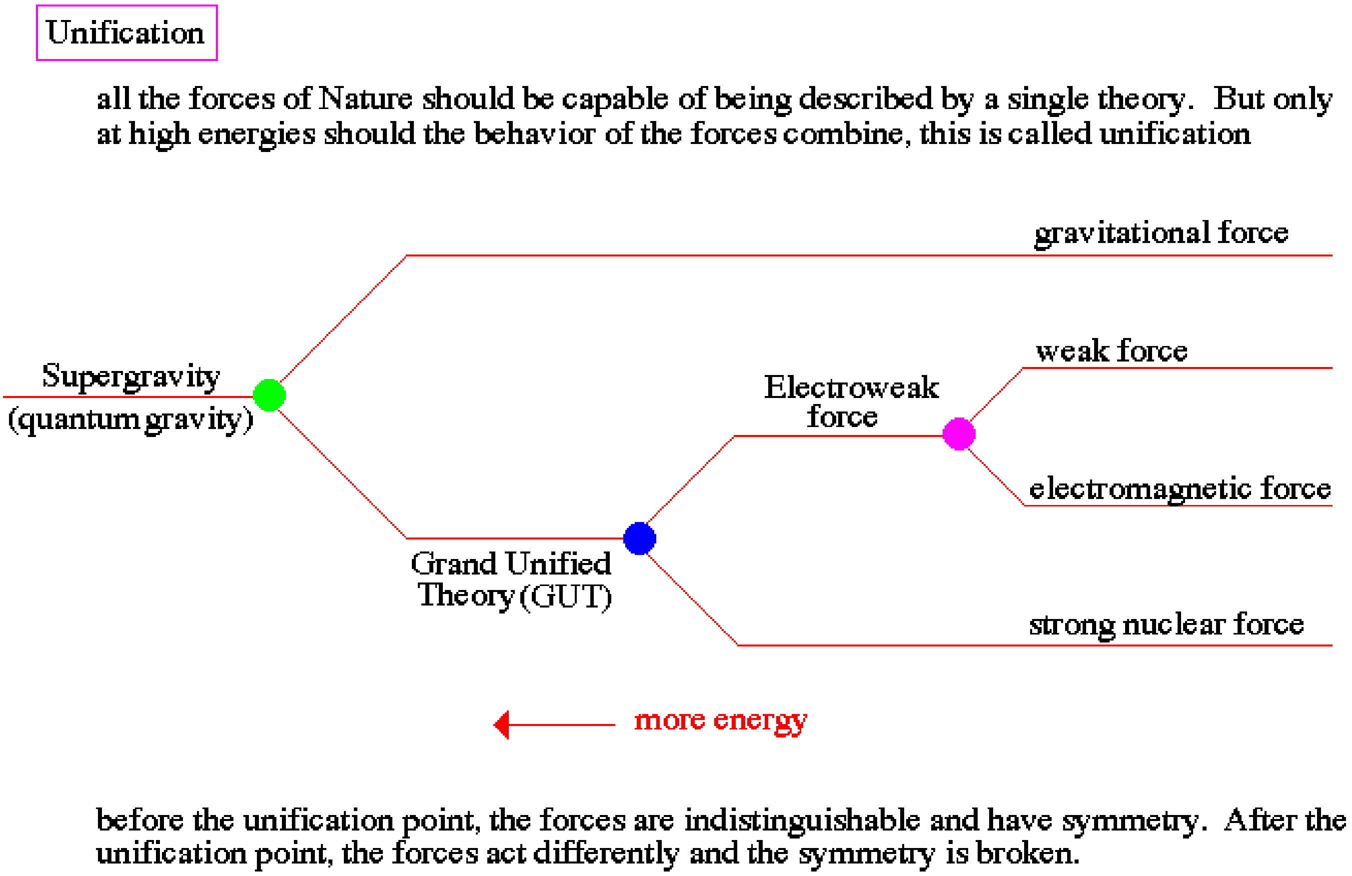



FORWARD



Unification:

One of the reasons our physics is incomplete during the Planck era is a lack of understanding of the unification of the forces of Nature during this time. At high energies and temperatures, the forces of Nature become symmetric. This means the forces resemble each other and become similar in strength, i.e. they unify.




An example of unification is to consider the interaction of the weak and electromagnetic forces. At low energy, photons and W,Z particles are the force carriers for the electromagnetic and weak forces. The W and Z particles are very massive and, thus, require alot of energy ($E=mc^2$). At high energies, photons take on similar energies to W and Z particles, and the forces become unified into the electroweak force.

There is the expectation that all the nuclear forces of matter (strong, weak and electromagnetic) unify at extremely high temperatures under a principle known as Grand Unified Theory, an extension of quantum physics using as yet undiscovered relationships between the strong and electroweak forces.

The final unification resolves the relationship between quantum forces and gravity (supergravity).

In the early Universe, the physics to predict the behavior of matter is determined by which forces are unified and the form that they take. The interactions just at the edge of the Planck era are ruled by supergravity, the quantum effects of mini-black holes. After the separation of gravity and nuclear forces, the spacetime of the Universe is distinct from matter and radiation.

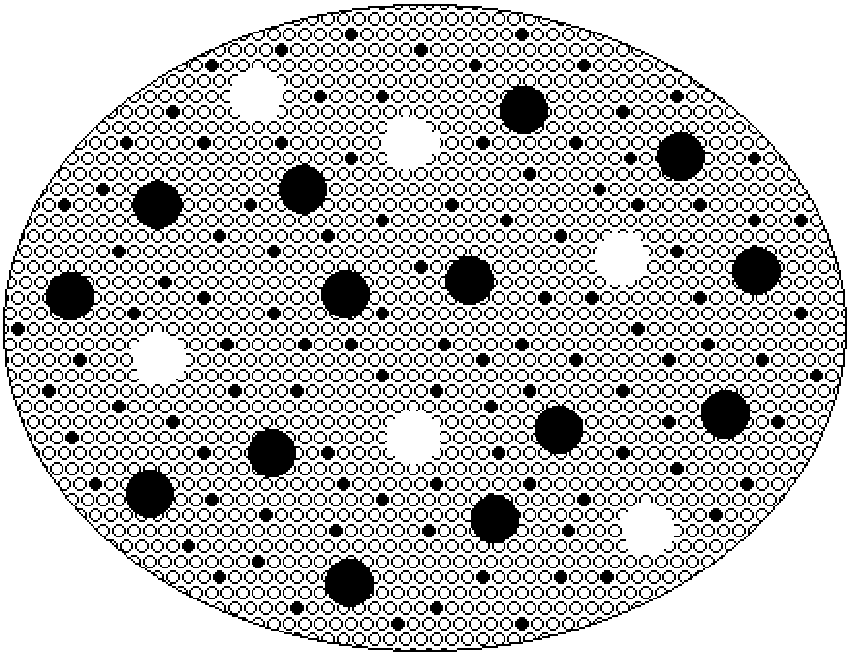
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Spacetime Foam :

The first moments after the Planck era are dominated by conditions were spacetime itself is twisted and distorted by the pressures of the extremely small and dense Universe.

Spacetime Foam

the immediate era after the Planck time is one of pressures and densities so high that spacetime itself is folded and meshed into foam of mini–black holes and wormholes



although the Planck time marks the beginning of time in the Universe, the convoluted nature of spacetime in this early phase, with numerous singularities and overlaping event horizons, makes it impossible for matter, photons or even causality to exist

Most of these black holes and wormholes are leftover from the Planck era, remnants of the event horizon that protected the cosmic singularity. These conditions are hostile to any organization or structure not protected by an event horizon. Thus, at this early time, black holes are the only units that can survive intact under these conditions, and serve as the first building blocks of structure in the Universe, the first `things' that have individuality.

Based on computer simulations of these early moments of the Universe, there is the prediction that many small, primordial black holes were created at this time with no large black holes (the Universe was too small for them to exist). However, due to Hawking radiation, the primordial black holes from this epoch have all decayed and disappeared by the present-day.

Matter arises at the end of the spacetime foam epoch as the result of strings, or loops in spacetime. The transformation is from ripping spacetime foam into black holes, which then transmute into elementary particles. Thus, there is a difference between something of matter and nothing of spacetime, but it is purely geometrical and there is nothing behind the geometry. Matter during this era is often called GUT matter to symbolize its difference from quarks and leptons and its existence under GUT forces.

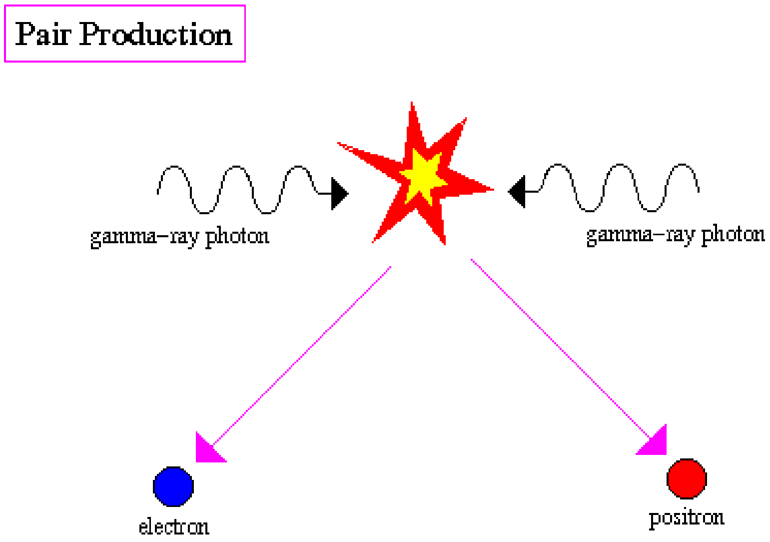
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Hawking Radiation:

Hawking, an English theoretical physicist, was one of the first to consider the details of the behavior of a black hole whose Schwarzschild radius was on the level of an atom. These black holes are not necessarily low mass, for example, it requires 1 billion tons of matter to make a black hole the size of

a proton. But their small size means that their behavior is a mix of quantum mechanics rather than relativity.

Before black holes were discovered it was know that the collision of two photons can cause pair production. This a direct example of converting energy into mass (unlike fission or fusion which turn mass into energy). Pair production is one of the primary methods of forming matter in the early Universe.



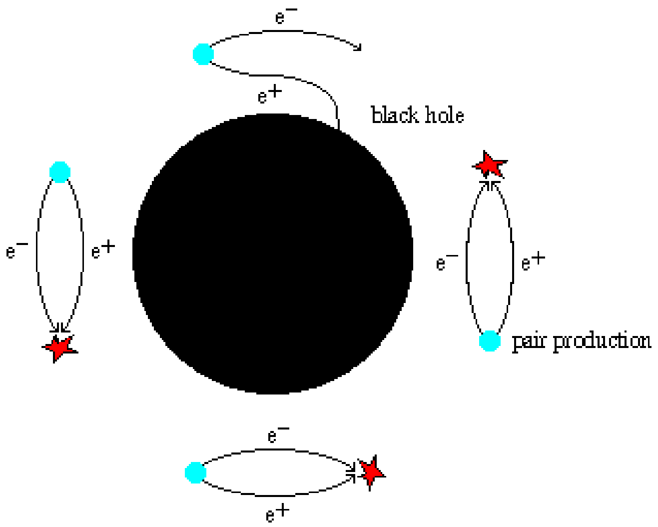

when two high energy gamma−ray photons collide, an electron/positron pair are produced (the energy is converted into mass, $E=mc^2$)

Note that pair production is symmetric in that a matter and antimatter particle are produced (an electron and an anti-electron (positron) in the above example).

Hawking showed that the strong gravitational gradients (tides) near black holes can also lead to pair production. In this case, the gravitational energy of the black hole is converted into particles.

## Hawking Radiation

**the strong gravitational field around a black hole causes pair production**



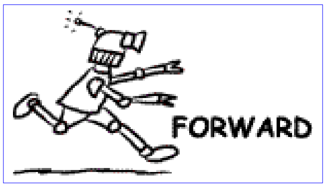

**if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass**

**the amount of mass lost is greater for small black holes, therefore quantum sized black holes disintegrate in very short timescales**

If the matter/anti-matter particle pair is produced below the event horizon, then particles remain trapped within the black hole. But, if the pair is produced above the event horizon, it is possible for one member to fall back into the black hole, the other to escape into space. Thus, the black hole can lose mass by a quantum mechanical process of pair production outside of the event horizon.

The rate of pair production is stronger when the curvature of spacetime is high. Small black holes have high curvature, so the rate of pair production is inversely proportional to the mass of the black hole (this means its faster for smaller black holes). Thus, Hawking was able to show that the mini or primordial black holes expected to form in the early Universe have since disintegrated, resolving the dilemma of where all such mini-black holes are today.

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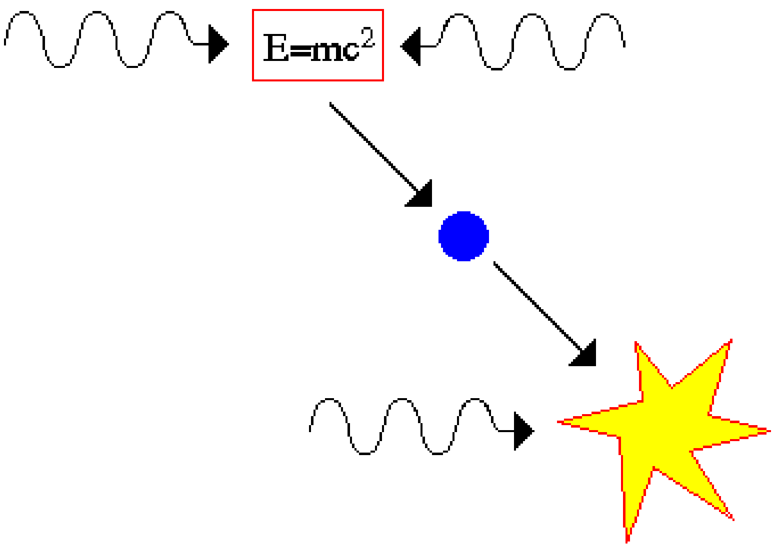

Symmetry Breaking:

In the early Universe, pressures and temperature prevented the permanent establishment of elementary particles. Even quarks and leptons were unable to form stable objects until the Universe had cooled beyond the supergravity phase. If the fundamental building blocks of Nature (elementary particles) or spacetime itself were not permanent then what remained the same? The answer is symmetry.

Matter Destruction

The formation of matter is inhibited in the early Universe due to collisions with high energy photons.

Matter forms when two photons collide, pair production.




But, when the energy density is high, the newly formed matter will quickly encounter another photon and be destroyed.

Often symmetry is thought of as a relationship, but in fact it has its own identical that is preserved during the chaos and flux of the early Universe. Even though virtual particles are created and destroyed, there is always a symmetry to the process. For example, for every virtual electron that is formed a virtual positron (anti-electron) is also formed. There is a time symmetric, mirror-like quality to every interaction in the early Universe.

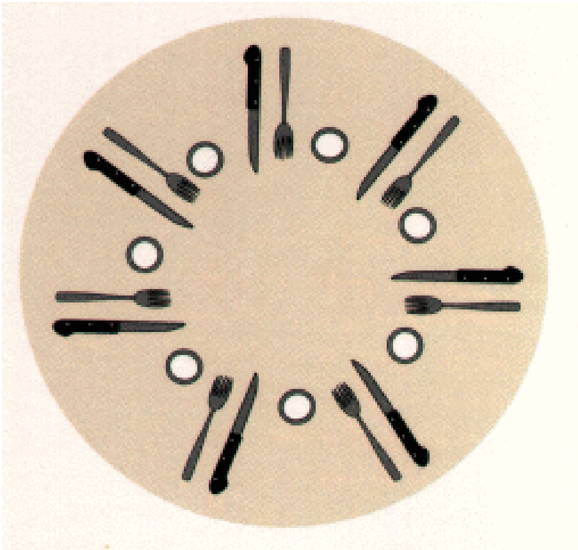
Symmetry also leads to conservation laws, and conservation laws limit the possible interactions between particles. Those imaginary processes that violate conservation laws are forbidden. So the existence of symmetry provides a source of order to the early Universe.

Pure symmetry is like a spinning coin. The coin has two states, but while spinning neither state is determined, and yet both states exist. The coin is in a state of both/or.

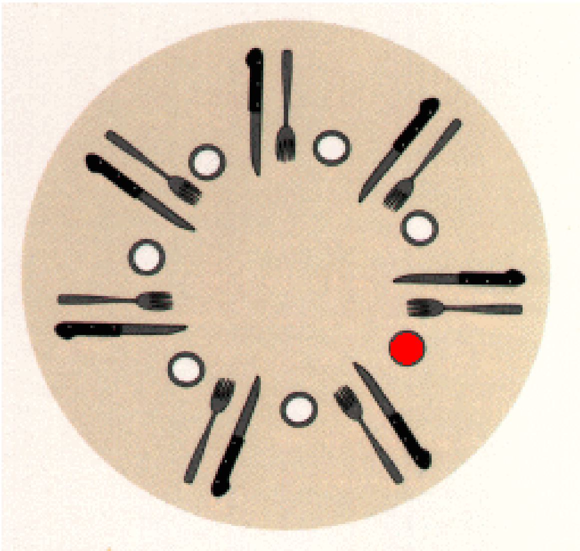
When the coin hits the floor the symmetry is broken (its either heads or tails) and energy is released in the process (the noise the coin makes as it hits the ground).

Symmetry Breaking

an example of symmetry is the place settings below



it is unclear which glass goes with any particular setting, until one is chosen

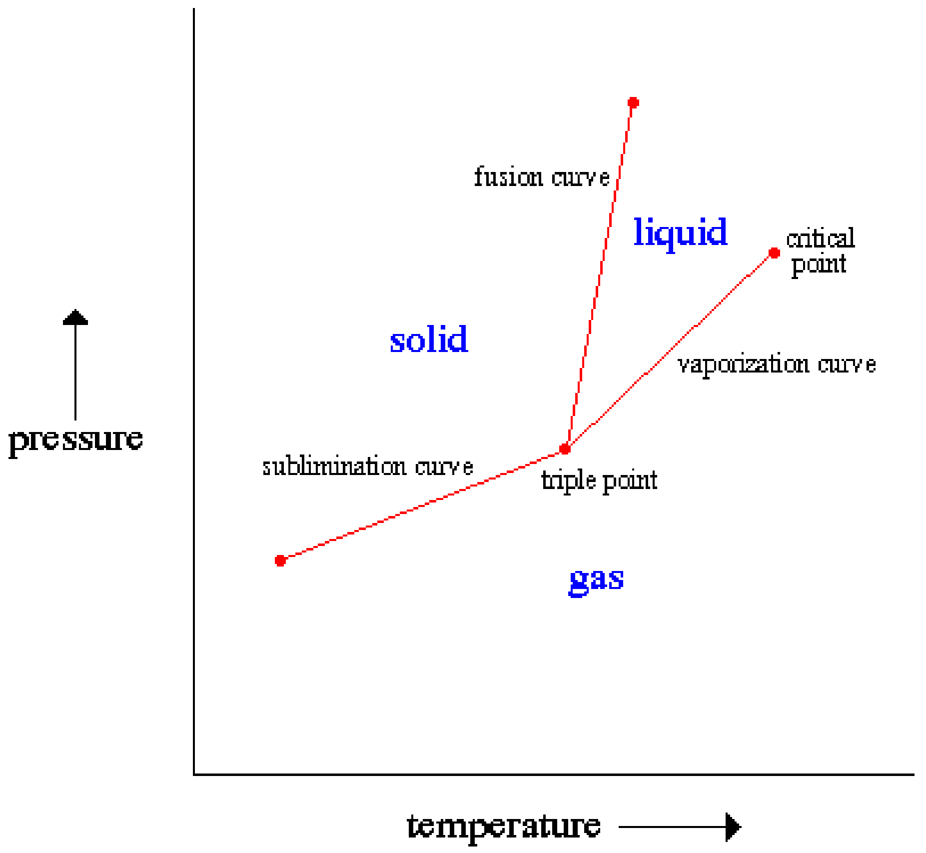


once a glass is chosen the symmetry is broken and the matching of glasses becomes unique

The effect of symmetry breaking in the early Universe was a series of phase changes, much like when ice melts to water or water boils to stream. A phase change is the dramatic change in the internal order of a substance. When ice melts, the increased heat breaks the bonds in the lattice of water molecules, and the ice no longer holds its shape.

Phase change in the early Universe occurs at the unification points of fundamental

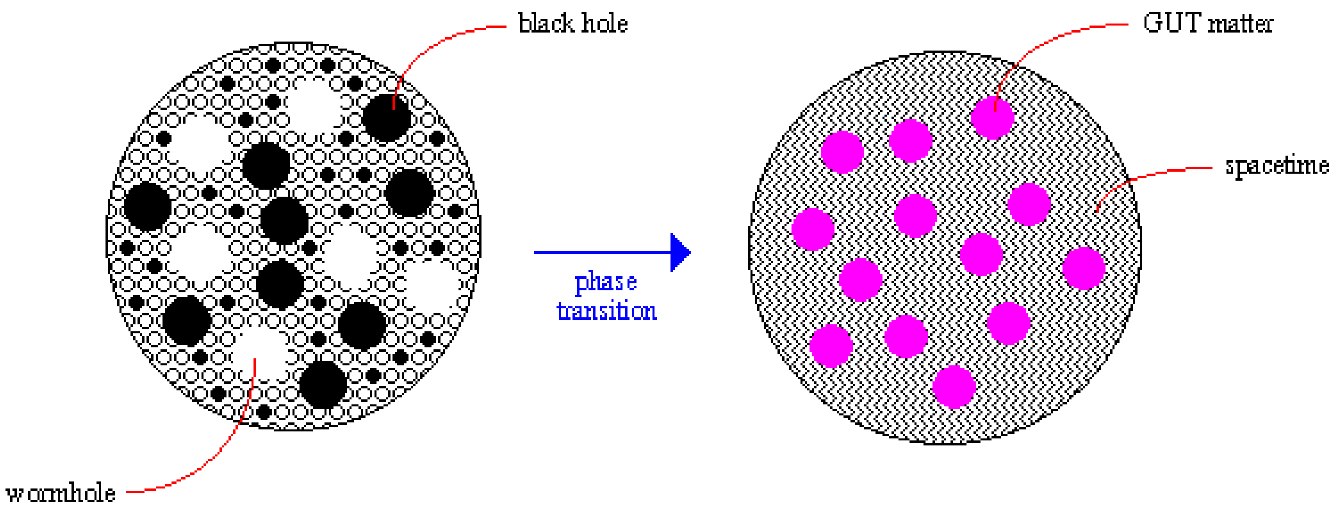
forces. The decoupling of those forces provides the energy input for phase changes in the Universe as a whole.




With respect to the Universe, a phase change during symmetry breaking is a point where the characteristics and the properties of the Universe make a radical shift. At the supergravity symmetry breaking, the Universe passed from the Planck era of total chaos to the era of spacetime foam. The energy release was used to create spacetime. During the GUT symmetry breaking, mass and spacetime separated and the energy released was used to create particles.

**Asymmetric Universe**

**the process of symmetry breaking changes the Universe from a symmetric case to an asymmetric case**




**the spacetime foam was a symmetric case of the distribution of black holes and wormholes. After the GUT symmetry breaking, the Universe became an asymmetric case of lumps of GUT matter in a uniform spacetime.**

Notice that as symmetry breaks, there is less order, more chaos. The march of entropy in the Universe apples to the laws of Nature as well as matter. The Universe at the time of the cosmic singularity was a time of pure symmetry, all the forces had equal strength, all the matter particles had the same mass (zero), spacetime was the same everywhere (although all twisted and convolved). As forces decouple, they lose their symmetry and the Universe becomes more disordered.

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Inflation:

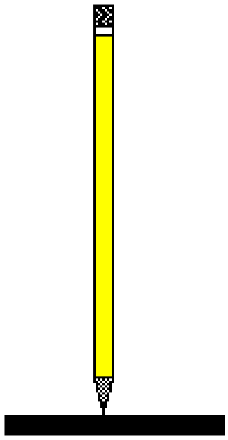
There are two major problems for the Big Bang model of the creation of the Universe. They are

- the flatness problem
- the horizon problem

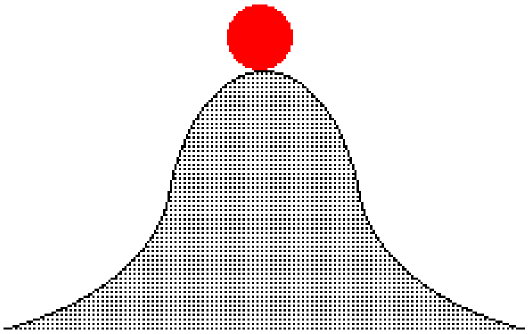
The flatness problem relates to the density parameter of the Universe, $\Omega$. Values for $\Omega$ can take on any number between 0.01 and 5 (lower than 0.01 and galaxies can't form, more than 5 and the Universe is younger than the oldest rocks). The measured value is near 0.2. This is close to an $\Omega$ of 1, which is strange because $\Omega$ of 1 is an unstable point for the geometry of the Universe.

## Instability

**there are many examples in Nature of balance points that are unstable**



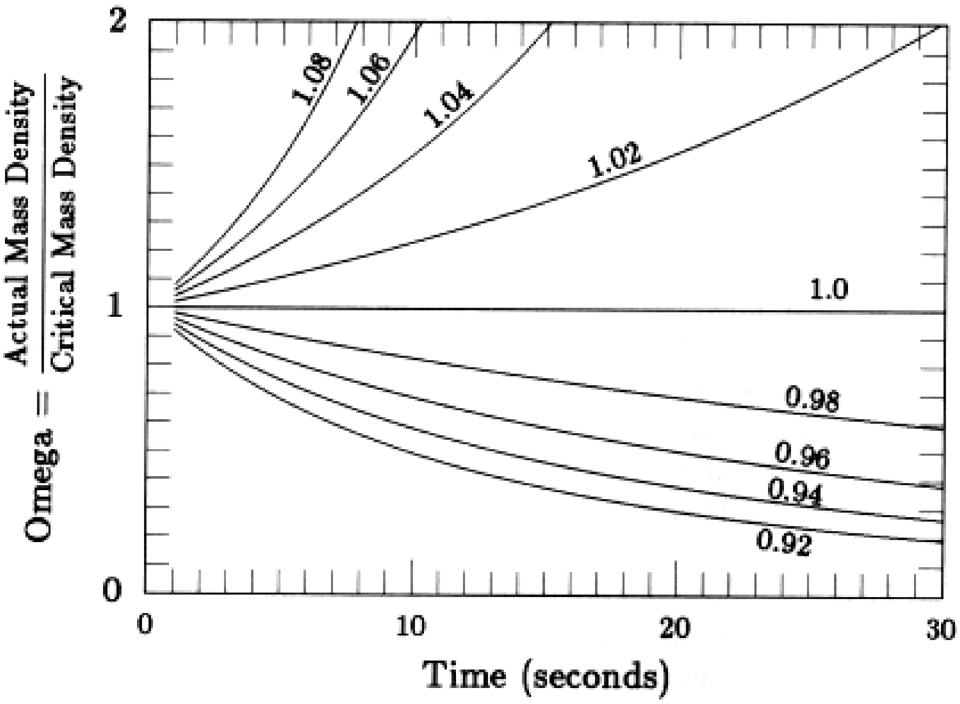
pencil on its point



ball at the top of a hill

**any perturbation on these objects causes a runaway to a more stable point**

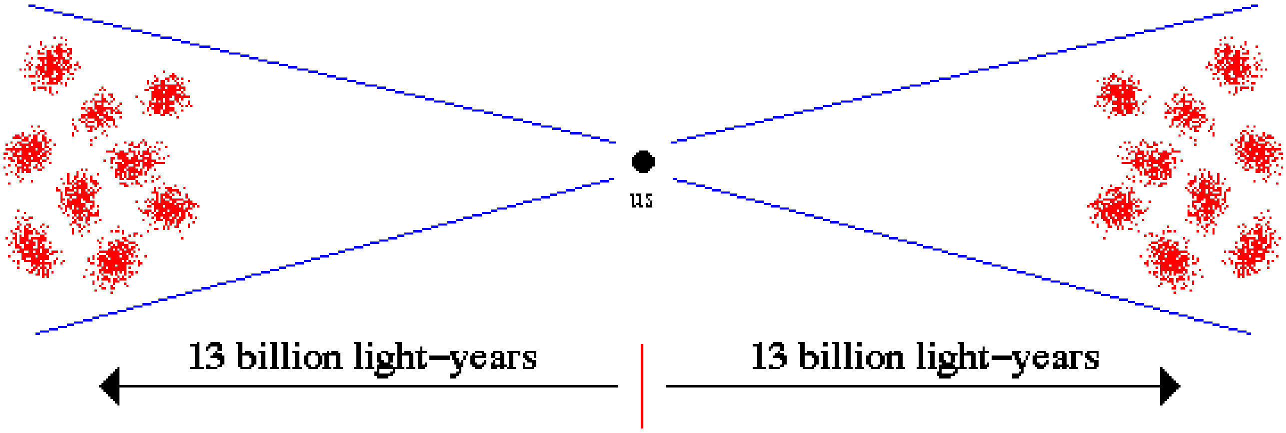
Values of Omega slightly below or above 1 in the early Universe rapidly grow to much less than 1 or much larger than 1 as time passes (like a ball at the top of a hill). After several billion years, Omega would have grown, or shrunk, to present-day values of much, much more, or much, much less than 1. So the fact that the measured value of 0.2 is so close to 1 that we expect to find that our measured value is too low and that the Universe must have a value of $\Omega$ exactly equal to 1 for stability. Therefore, the flatness problem is that some mechanism is needed to produce a value for $\Omega$ to be exactly one (to balance the pencil). A Universe of $\Omega$ of 1 is a flat Universe.




The horizon problem concerns the fact that the Universe is isotropic. No matter what distant corners of the Universe you look at, the sizes and distribution of objects is exactly the same (see the Cosmological Principle). But there is no reason to expect this since opposite sides of the Universe are not causally connected, any information that is be transmitted from one side would not reach the other side in the lifetime of the Universe (limited to travel at the speed of light).

## Horizon Problem

the number and size of density fluctuations on both sides of the sky are similar, yet they are separated by a distance that is greater than the speed of light times the age of the Universe, i.e. they should have no knowledge of each other by special relativity



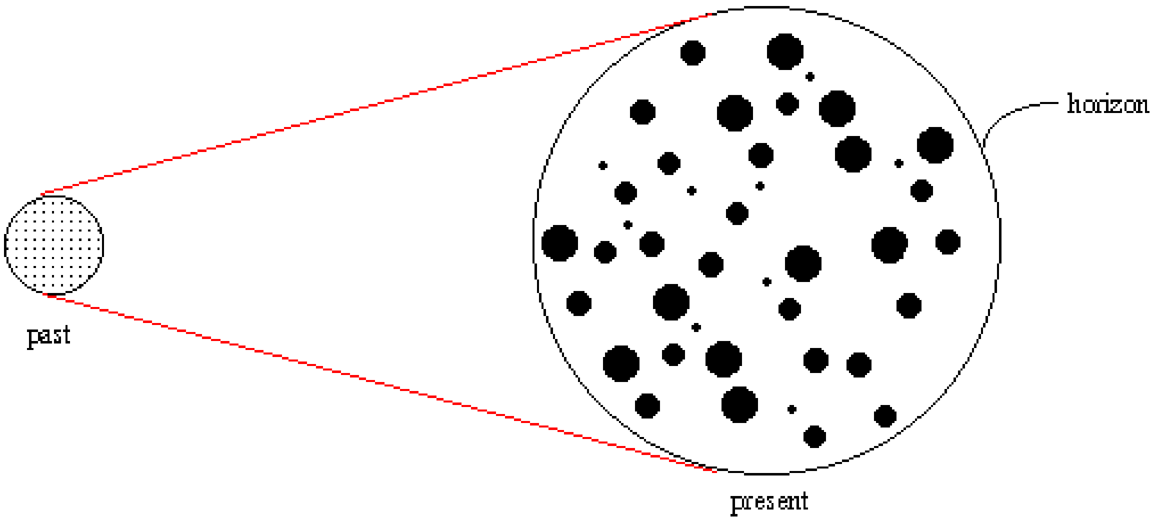

at some time in the early Universe, all parts of spacetime were causally connected, this must have happened after the spactime foam era, and before the time where thermalization of matter occurred.

All of the Universe has an origin at the Big Bang, but time didn't exist until after the Planck era. By the end of that epoch, the Universe was already expanding so that opposite sides could not be causally connected.

The solution to both the flatness and horizon problems is found during a phase of the Universe called the inflation era. During the inflation era the Universe expanded a factor of $10^{54}$, so that our horizon now only sees a small piece of what was once the total Universe from the Big Bang.

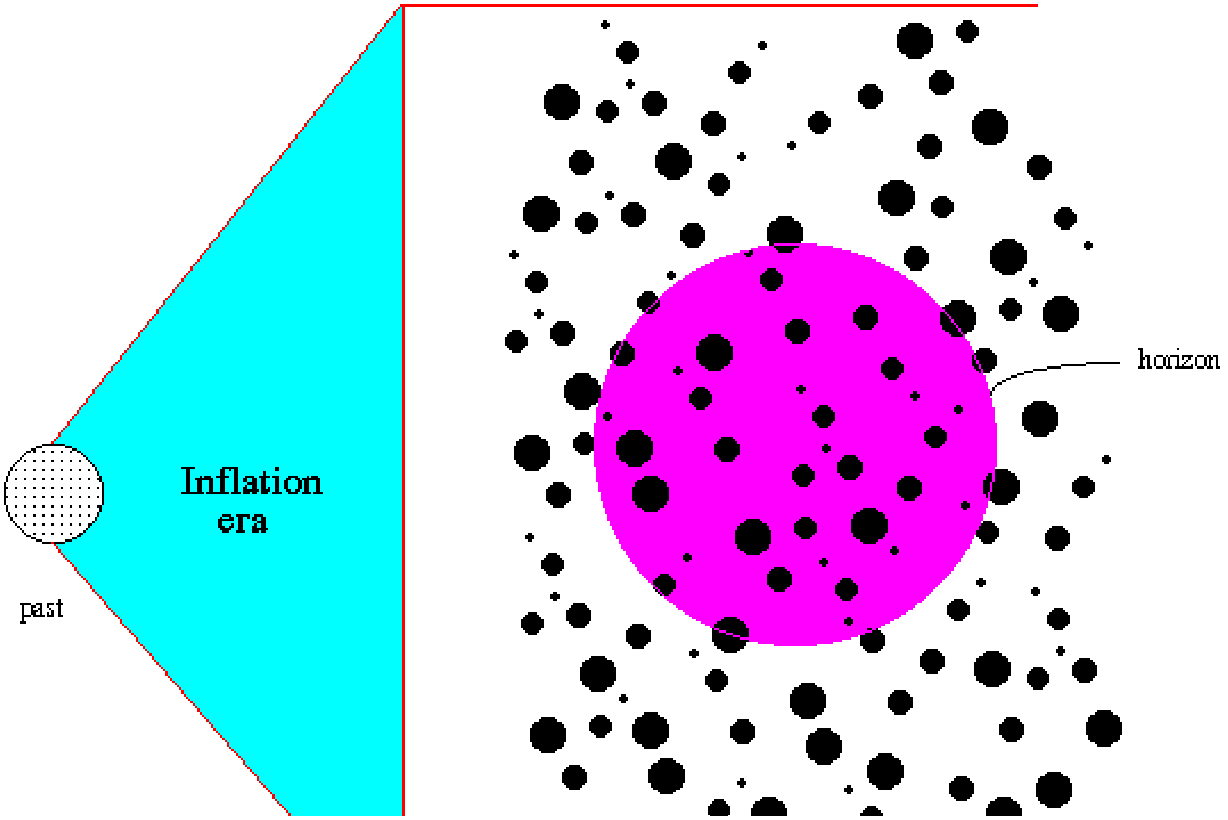
## Normal Expansion

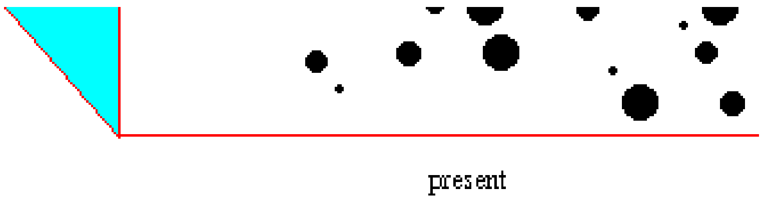
normal expansion is when the Universe expands at less than the speed of light such that all the Universe is within our horizon either now or sometime in the future




## Inflation

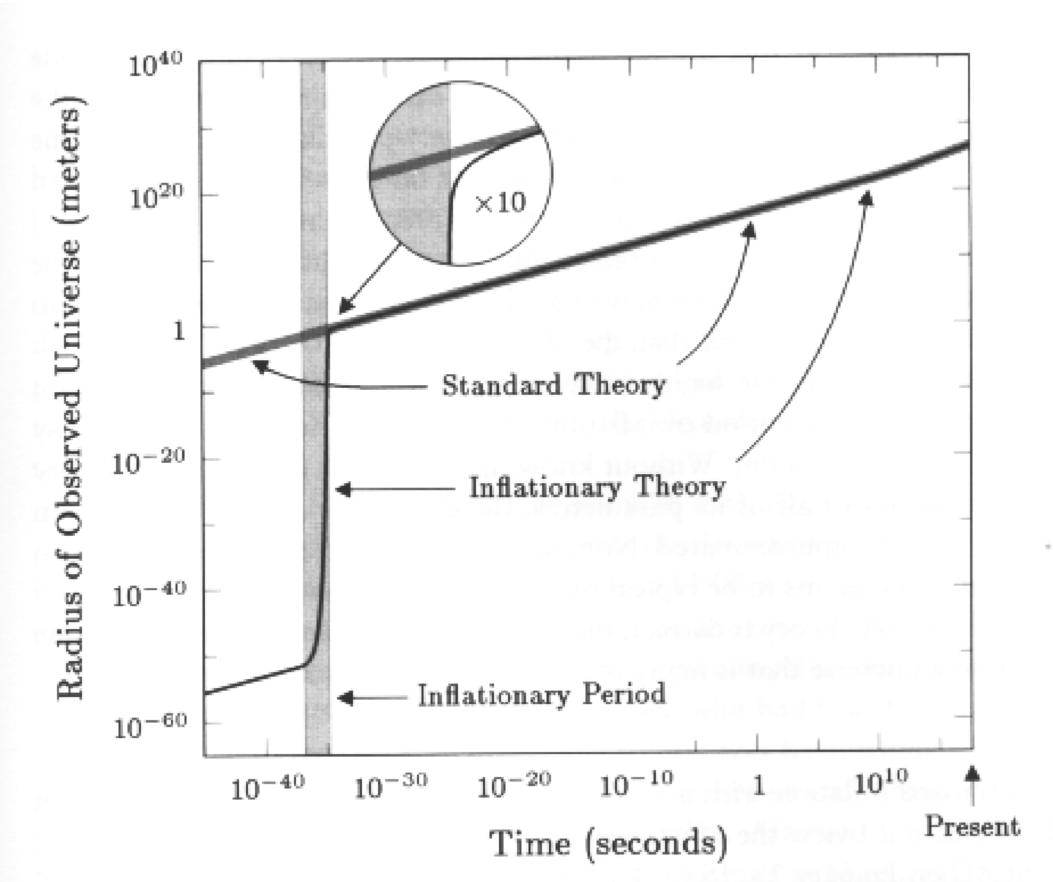
under inflationary cosmology, the Universe underwent a phase change at the GUT era and expanded faster than the speed of light (the spacetime itself expanded, so there is no violation of special relativity)






**the result is that only a small part of the original Big Bang is within our horizon, what we call our Universe.**

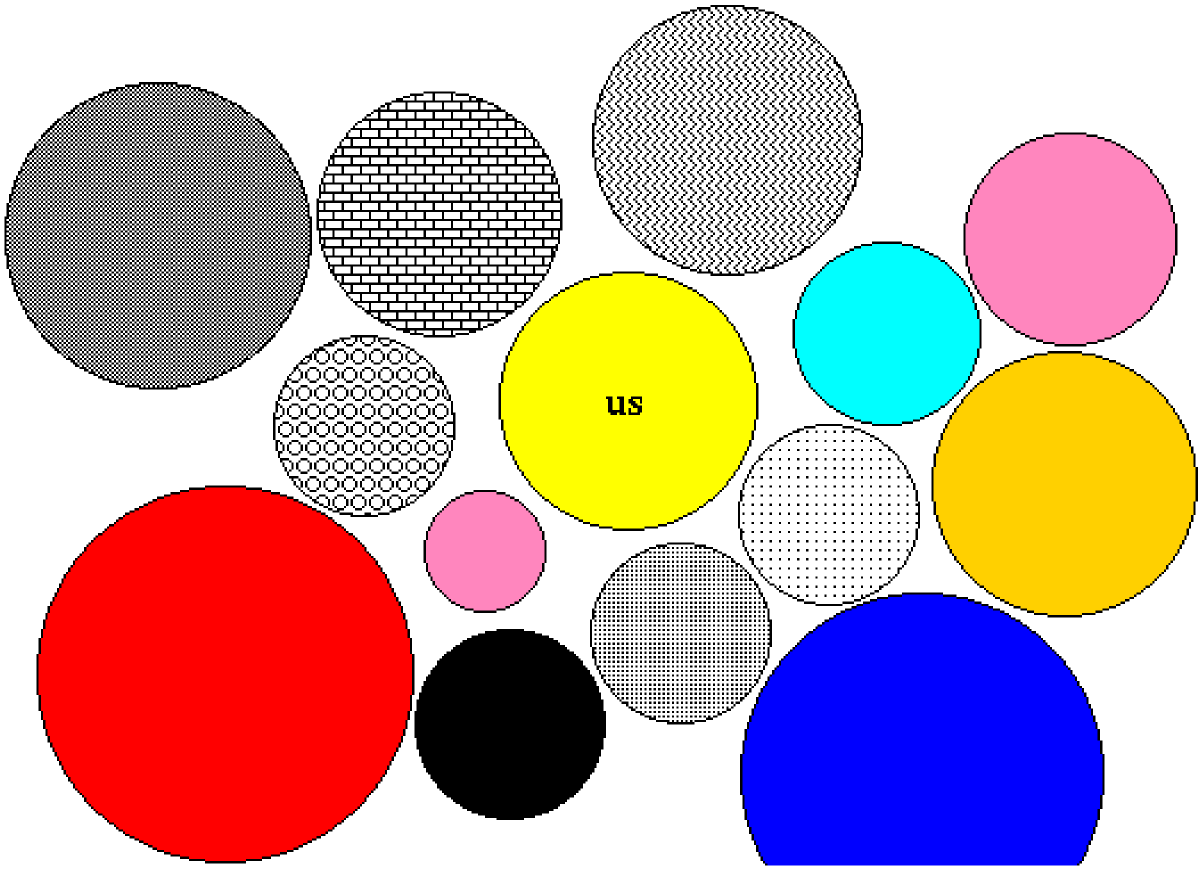
The cause of the inflation era was the symmetry breaking at the GUT unification point. At this moment, spacetime and matter separated and a tremendous amount of energy was released. This energy produced an overpressure that was applied not to the particles of matter, but to spacetime itself. Basically, the particles stood still as the space between them expanded at an exponential rate.




Note that this inflation was effectively at more than the speed of light, but since the expansion was on the geometry of the Universe itself, and not the matter, then there is no violation of special relativity. Our visible Universe, the part of the Big Bang within our horizon, is effectively a `bubble' on the larger Universe. However, those other bubbles are not physically real since they are outside our horizon. We can only relate to them in an imaginary, theoretical sense. They are outside our horizon and we will never be able to communicate with those other bubble universes.

Bubble Universes

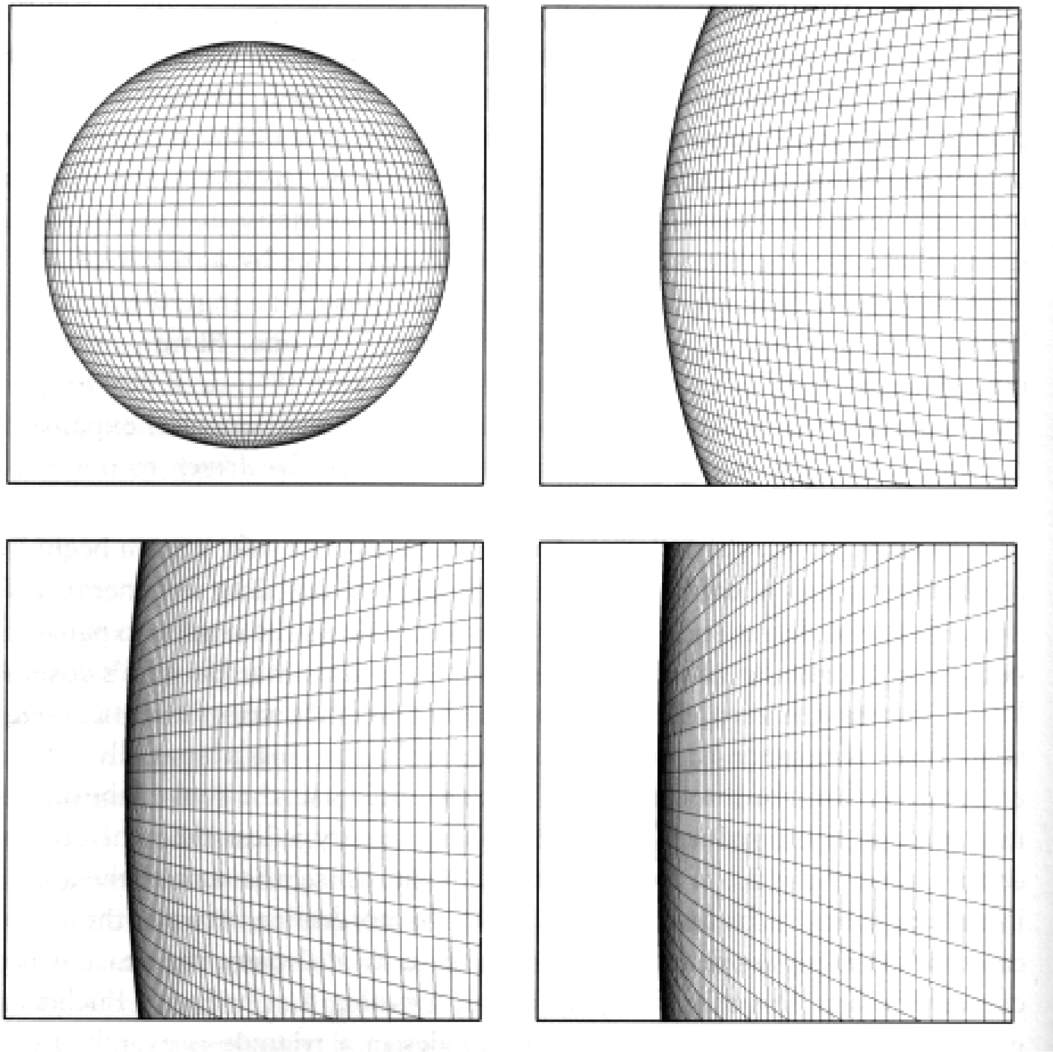
after the inflation era, our Universe became just one of many bubbles in the Big Bang substratum

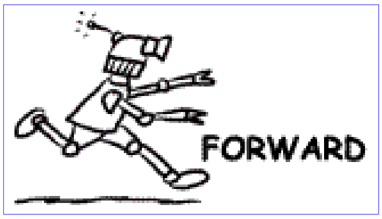



although these other bubble universes may exist theoretically, we will never be able to observe or communicate with them since they are outside our horizon

Notice how this solves the horizon problem in that our present Universe was simply a small piece of a larger Big Bang universe that was all in causal connection before the inflation era. Other bubble universes might have very different constants and evolutionary paths, but our Universe is composed of a small, isotropic slice of the bigger Big Bang universe.

Inflation also solves the flatness problem because of the exponential growth. Imagine a highly crumbled piece of paper. This paper represents the Big Bang universe before inflation. Inflation is like zooming in of some very, very small section of the paper. If we zoom in to a small enough scale, the paper will appear flat. Our Universe must be exactly flat for the same reason, it is a very small piece of the larger Big Bang universe.




FORWARD


BACKWARD

Anthropic Principle :

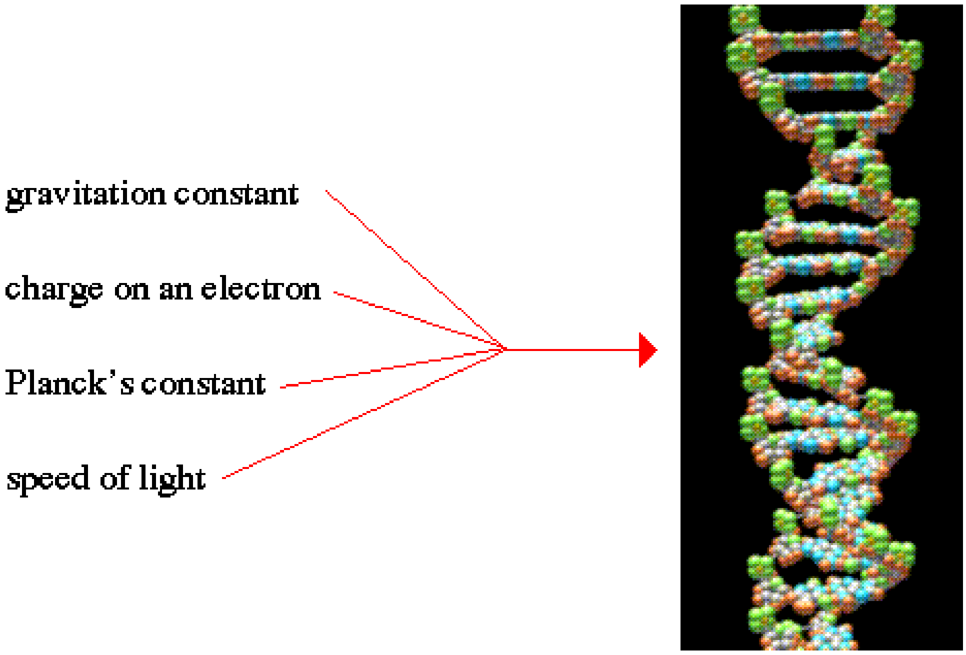
In the past 20 years our understanding of physics and biology has noted a peculiar specialness to our Universe, a specialness with regard to the existence of intelligent life. This sends up warning signs from the Copernican Principle, the idea that no scientific theory should invoke a special place or aspect to humans.

All the laws of Nature have particular constants associated with them, the gravitational constant, the speed of light, the electric charge, the mass of the electron, Planck's constant from quantum mechanics. Some are derived from physical laws (the speed of light, for example, comes from Maxwell's equations). However, for most, their values are arbitrary. The laws would still operate if the constants had different values, although the resulting interactions would be radically different.

Examples:

- gravitational constant: Determines strength of gravity. If lower than stars would have insufficient pressure to overcome Coulomb barrier to start thermonuclear fusion (i.e. stars would not shine). If higher, stars burn too fast, use up fuel before life has a chance to evolve.
- strong force coupling constant: Holds particles together in nucleus of atom. If weaker than multi-proton particles would not hold together, hydrogen would be the only element in the Universe. If stronger, all elements lighter than iron would be rare. Also radioactive decay would be less, which heats core of Earth.
- electromagnetic coupling constant: Determines strength of electromagnetic force that couples electrons to nucleus. If less, than no electrons held in orbit. If stronger, electrons will not bond with other atoms. Either way, no molecules.

All the above constants are critical to the formation of the basic building blocks of life. And, the range of possible values for these constants is very narrow, only about 1 to 5% for the combination of constants.



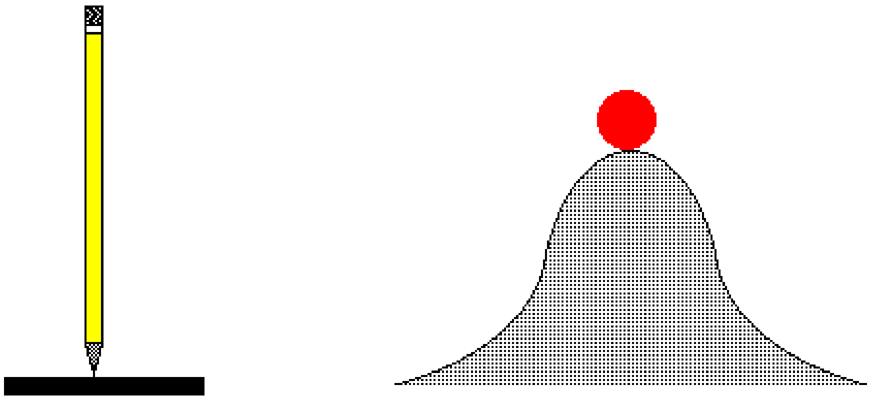

It is therefore possible to imagine whole different kinds of universes with different constants. For example, a universe with a lower gravitational constant would have a weaker force of gravity, where stars and planets might not form. Or a universe with a high strong force which would inhibit thermonuclear fusion, which would make the luminosity of stars be much lower, a darker universe, and life would have to evolve without sunlight.

The situation became worst with the cosmological discoveries of the 1980's. The two key cosmological parameters are the cosmic expansion rate (Hubble's constant, which determines the age of the Universe) and the cosmic density parameter ($\Omega$), which determines the acceleration of the Universe and its geometry).

The flatness problem relates to the density parameter of the Universe, $\Omega$. Values for $\Omega$ can take on any number, but it has to be between 0.01 and 5. If $\Omega$ is less than 0.01 the Universe is expanding so fast that the Solar System flys apart. And $\Omega$ has to be less than 5 or the Universe is younger than the oldest rocks. The measured value is near 0.2. This is close to an $\Omega$ of 1, which is strange because $\Omega$ of 1 is an unstable critical point for the geometry of the Universe.

**Instability**

**there are many examples in Nature of balance points that are unstable**



pencil on its point          ball at the top of a hill

**any perturbation on these objects causes a runaway to a more stable point**

Values slightly below or above 1 in the early Universe rapidly grow to much less than 1 or much larger than 1 (like a ball at the top of a hill). So the fact that the measured value of 0.2 is so close to 1 that we expect to find in the future that our measured value is too low and that the Universe has a value of $\Omega$ exactly equal to 1 for stability.

This dilemma of the extremely narrow range of values for physical constants is allowed for the evolution of conscious creatures, such as ourselves, is called the anthropic principle, and has the form:

Anthropic Principle: The Universe must have those properties which allow life to develop within it at some stage in its history.

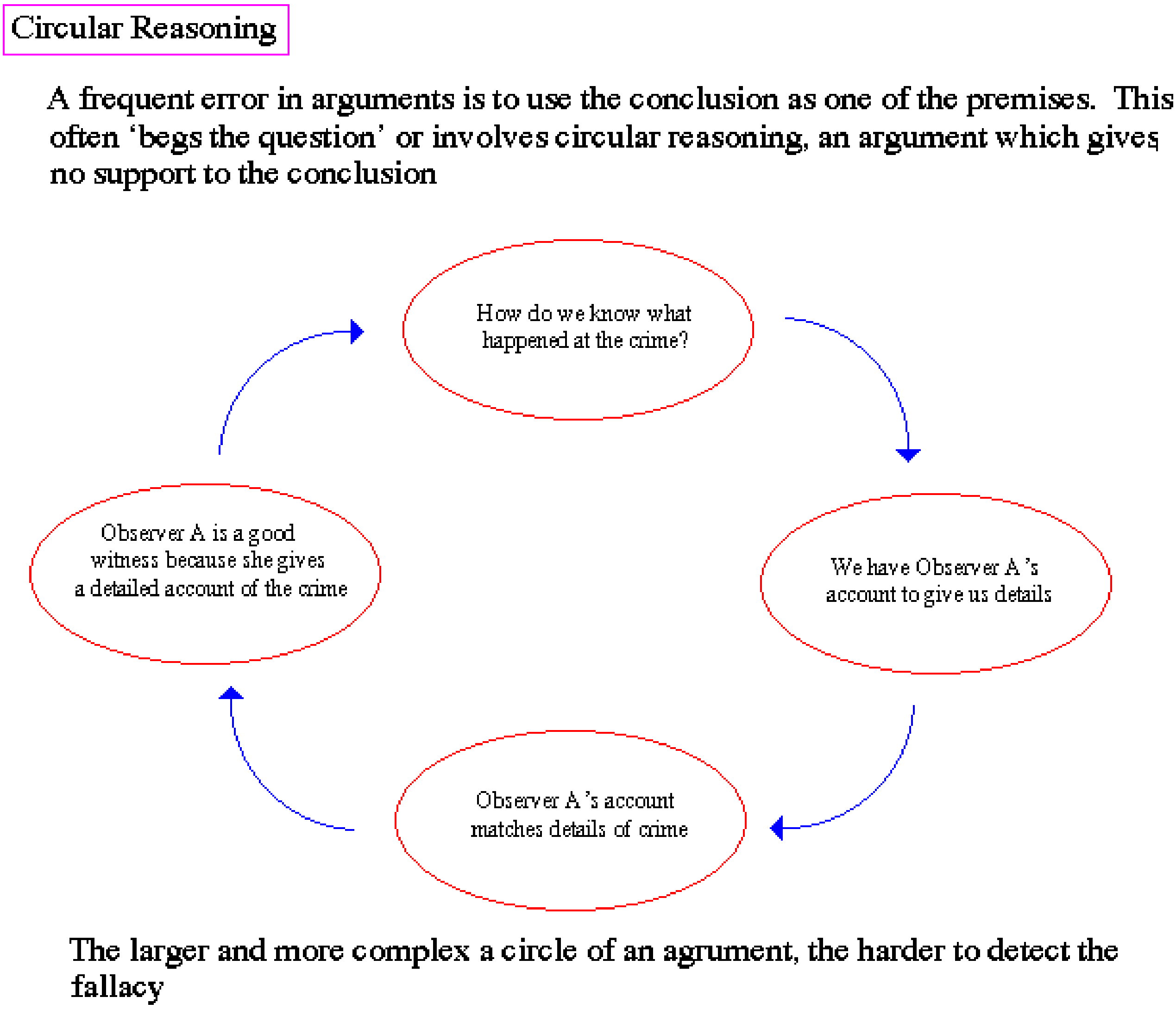
There are three possible alternatives from the anthropic principle;

1. There exists one possible Universe `designed' with the goal of generating and sustaining `observers' (theological universe). Or...
2. Observers are necessary to bring the Universe into being (participatory universe). Or...
3. An ensemble of other different universes is necessary for the existence of our Universe (multiple universes)

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Anthropic Principle and Circular Reasoning :

The usual criticism of any form of the anthropic principle is that it is guilty of a tautology or circular reasoning.




With the respect to our existence and the Universe, the error in reasoning is that because we are here, it must be possible that we can be here. In other words, we exist to ask the question of the anthropic principle. If we didn't exist then the question could not be asked. So there is nothing special to the anthropic principle, it simply states we exist to ask questions about the Universe.

An example of this style of question is whether life is unique to the Earth. There are many special qualities to the Earth (proper mass, distance from Sun for liquid water, position in Galaxy for heavy elements from nearby supernova explosion). But, none of these characteristics are unique to the Earth. There may exists hundreds to thousands of solar systems with similar characteristics where life would be possible, if not inevitable. We simply live on one of them, and we would not be capable of living on any other world.

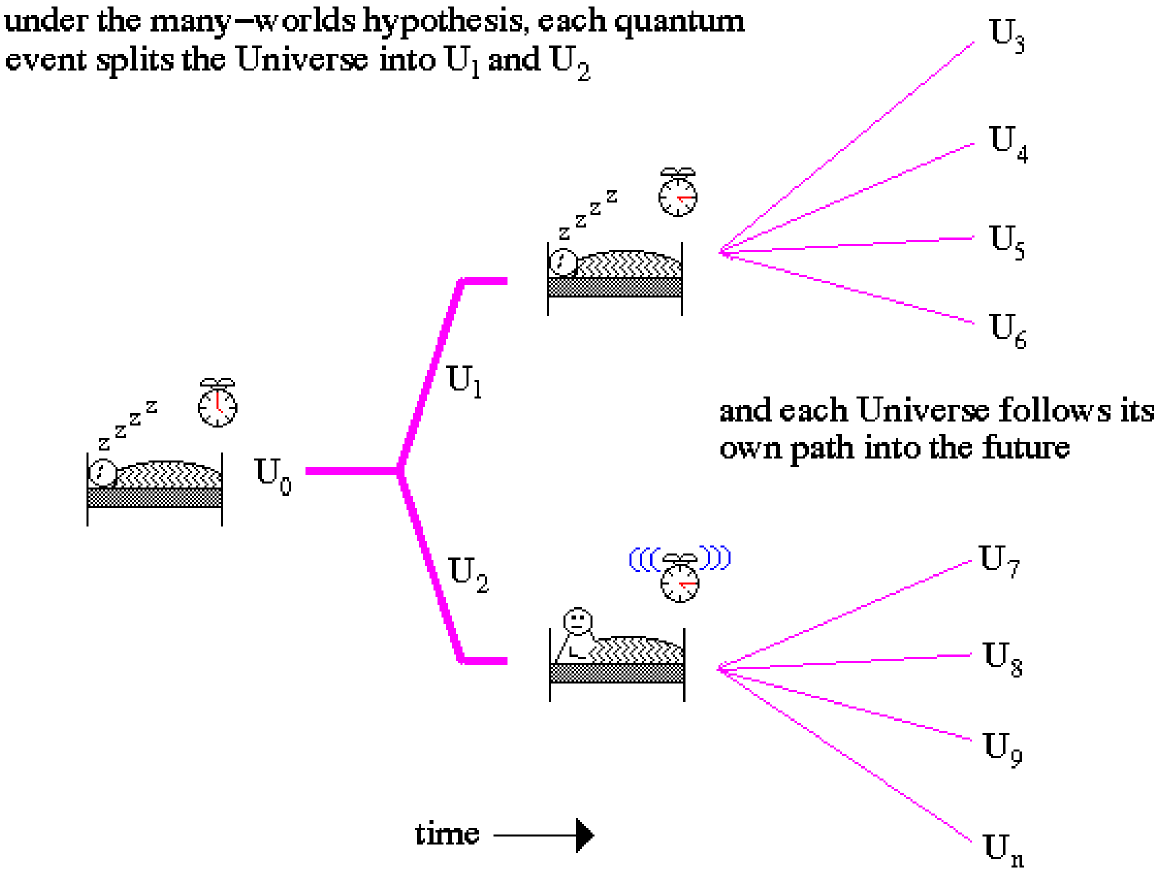
This solution is mildly unsatisfying with respect to physical constants since it implies some sort-of lottery system for the existence of life, and we have no evidence of previous Universes for the randomness to take place.

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Anthropic Principle and Many-Worlds Hypothesis:

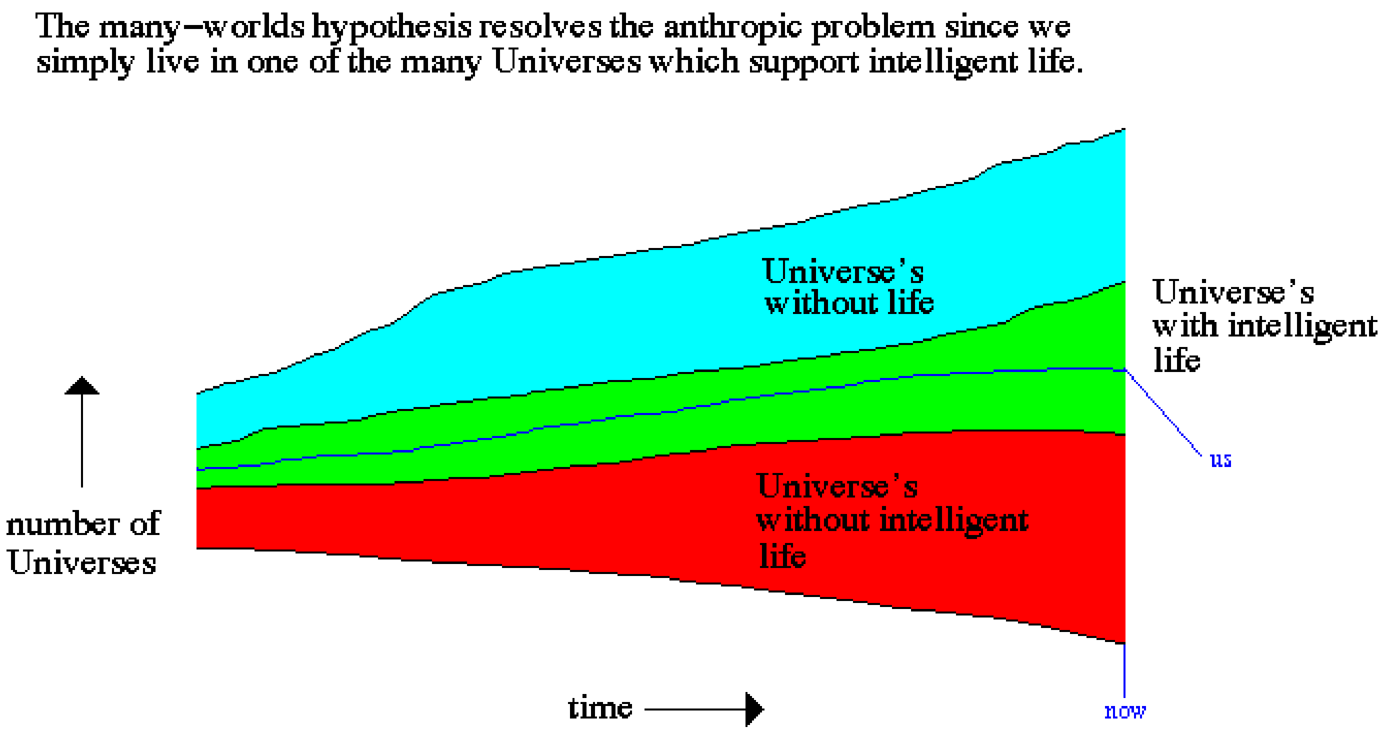
Another solution to the anthropic principle is that all possible universes, that can be imagined under the current laws of Nature, are possible and do have an existence as quantum

superpositions.




all the possible Universe's exist, but none can communicate with another.

This is the infamous many-worlds hypothesis used to explain how the position of an electron can be fuzzy or uncertainty. Its not uncertain, it actual exists in all possible positions, each one having its own separate and unique universe. Quantum reality is explained by the using of infinite numbers of universes where every possible realization of position and energy of every particle actually exists.



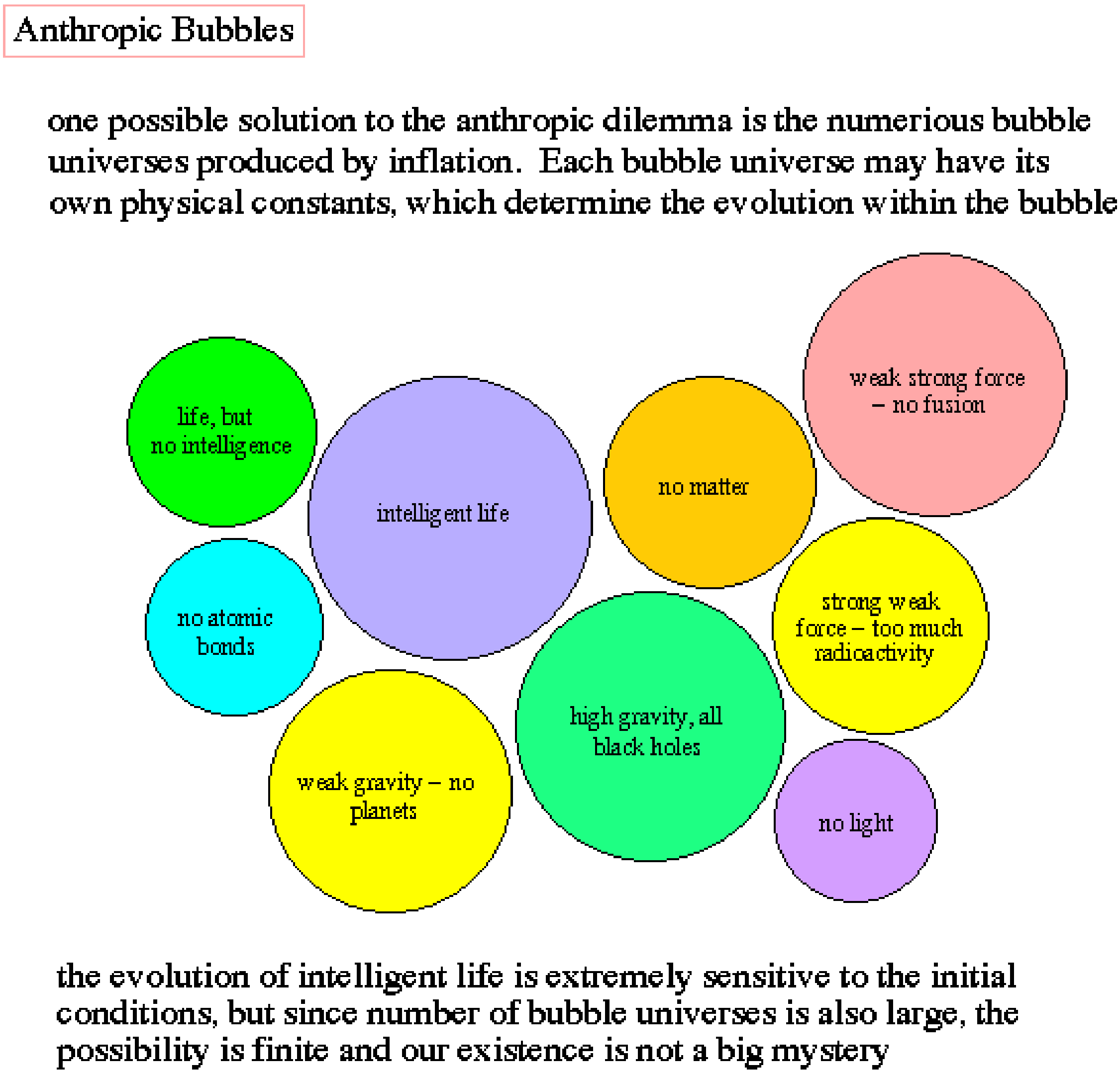

With respect to the anthropic principle, we simply exist in one of the many universes where intelligent life is possible and did evolve. There are many other universes where this is not the case, existing side by side with us in some super-reality of the many-worlds. Since the many-worlds hypothesis lacks the ability to test the existence of these other universes, it is not falsifiable and, therefore, borders on pseudo-science.

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Anthropic Principle and Inflation :

Another avenue to understanding the anthropic principle is through inflation. Inflation theory shows that the fraction of the volume of the Universe with given properties does not depend on time. Each part evolves with time, but the Universe as a whole may be stationary and the properties of the parts do not depend on the initial conditions.

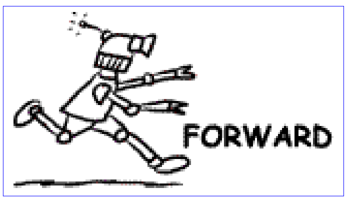
During the inflation era, the Universe becomes divided into exponentially large domains containing matter in all possible `phases'. The distribution of volumes of different domains may provide some possibility to find the ``most probable'' values for universal constants. When the Universe inflated, these different domains separated, each with its own values for physical constants.




Inflation's answer to the anthropic principle is that multiple universes were created from the Big Bang. Our Universe had the appropriate physical constants that lead to the evolution of intelligent life. However, that evolution was not determined or required. There may exist many other universes with similar conditions, but where the emergent property of life or intelligence did not develop.

Hopefully a complete Theory of Everything will resolve the `how' questions on the origin of physical constants. But a complete physical theory may be lacking the answers to `why' questions, which is one of the reasons that modern science is in a crisis phase of development, our ability to understand `how' has outpaced our ability to answer if we `should'.

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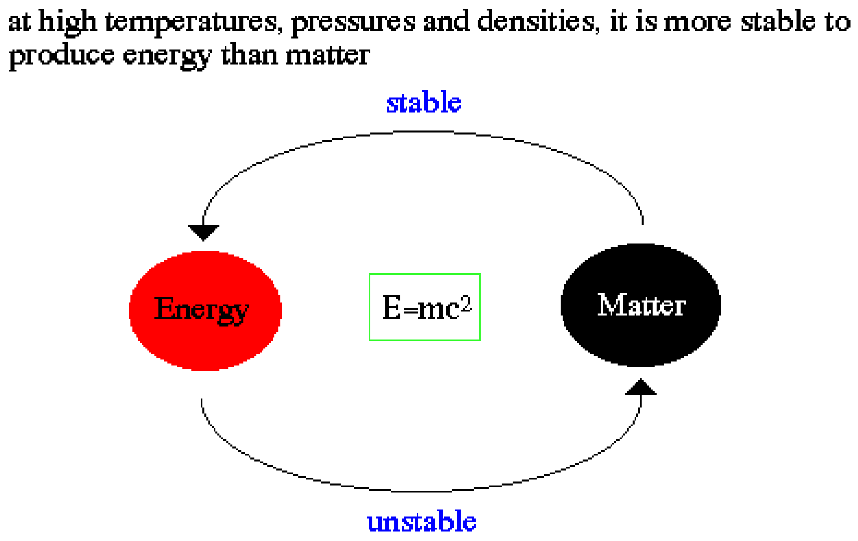





GUT matter :

Spacetime arrives when supergravity separates into the combined nuclear forces (strong, weak, electromagnetic) and gravitation. Matter makes its first appearance during this era as a composite form called Grand Unified Theory or GUT matter. GUT matter is a combination of what will become leptons, quarks and photons. In other words, it contains all the superpositions of future normal matter. But, during the GUT era, it is too hot and violent for matter to survive in the form of leptons and quarks.

Why can't matter remain stable at this point in the Universe's evolution? This involves the concept of equilibrium, the balance between particle creation and annihilation.



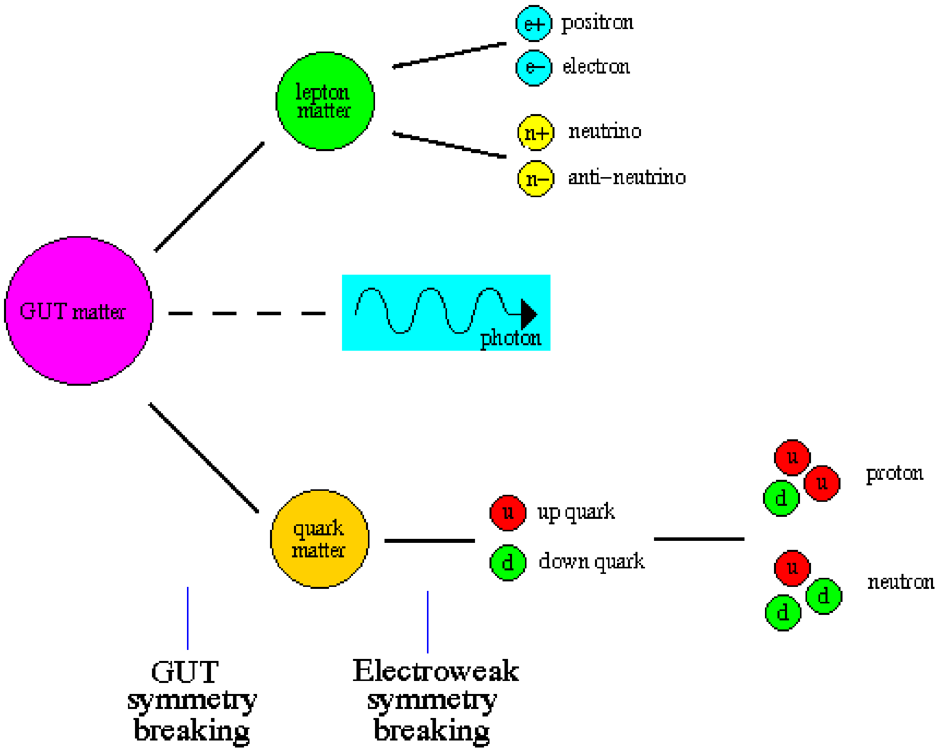

During pair production, energy is converted directly into mass in the form of a matter and anti-matter particle pair. The simplest particles are, of course, leptons such as an electron/positron pair. However, in high energy regimes, such as the early Universe, the conversion from energy to mass is unstable compared to the more probable mass to energy conversion (because the created mass must be so high in mass to match the energy used). In other words, when temperatures are high, matter is unstable and energy is stable.

Any matter that forms in the early Universe quickly collides with other matter or energy and is converted back into energy. The matter is in equilibrium with the surrounding energy and at this time the Universe is energy or radiation-dominated.

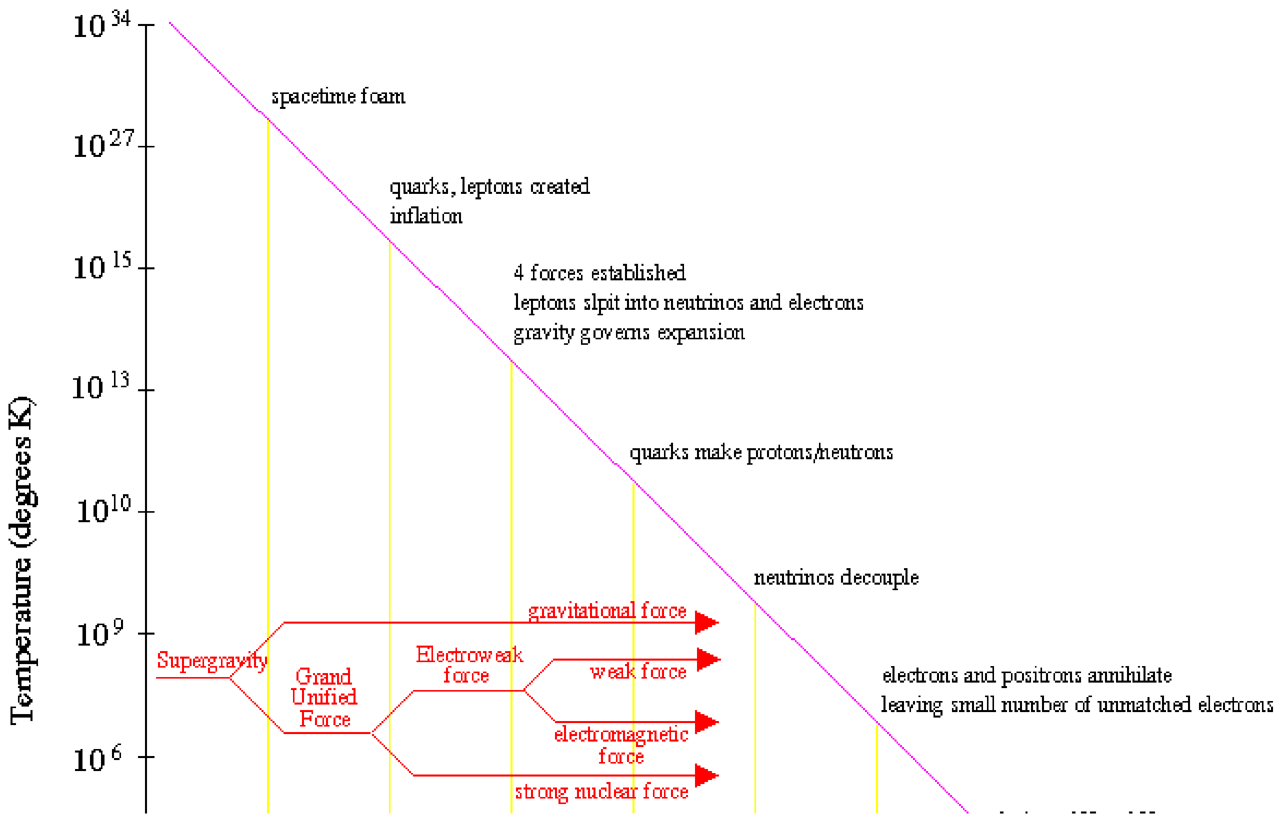
The type of matter that is created is dependent on the energy of its surroundings. Since the temperatures are so high in the early Universe, only very massive matter (= high energy) can form. However, massive particles are also unstable particles. As the Universe expands and cools, more stable, less massive forms of matter form.

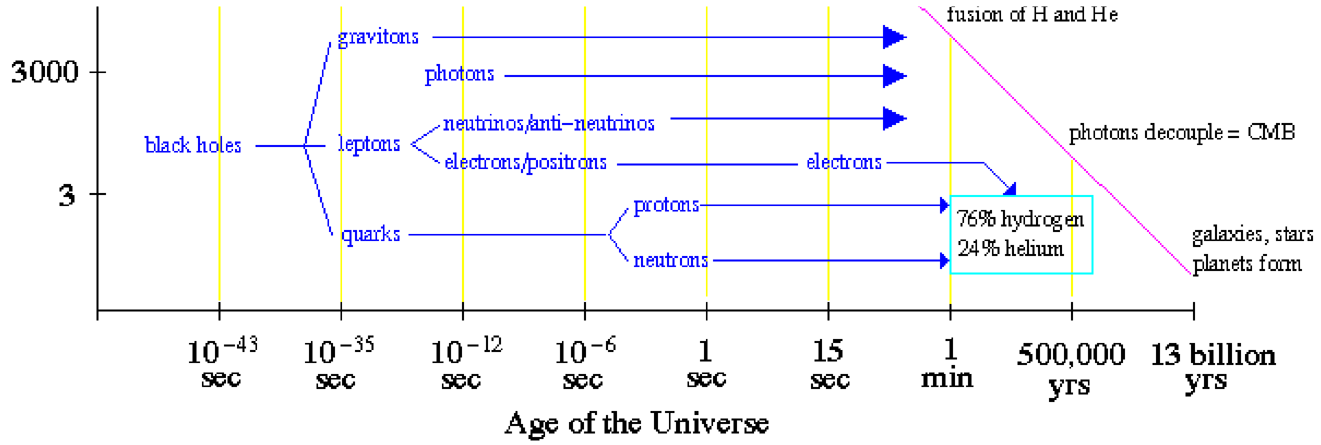
Matter Evolution

as the Universe expanded and cooled, matter began to condense starting with massive GUT matter. Each symmetry breaking produces a phase change and different forms of matter appear




As the Universe expands, matter is able to exist for longer periods of time without being broken down by energy. Eventually quarks and leptons are free to combine and form protons, neutrons and atoms, the ordinary matter of today.



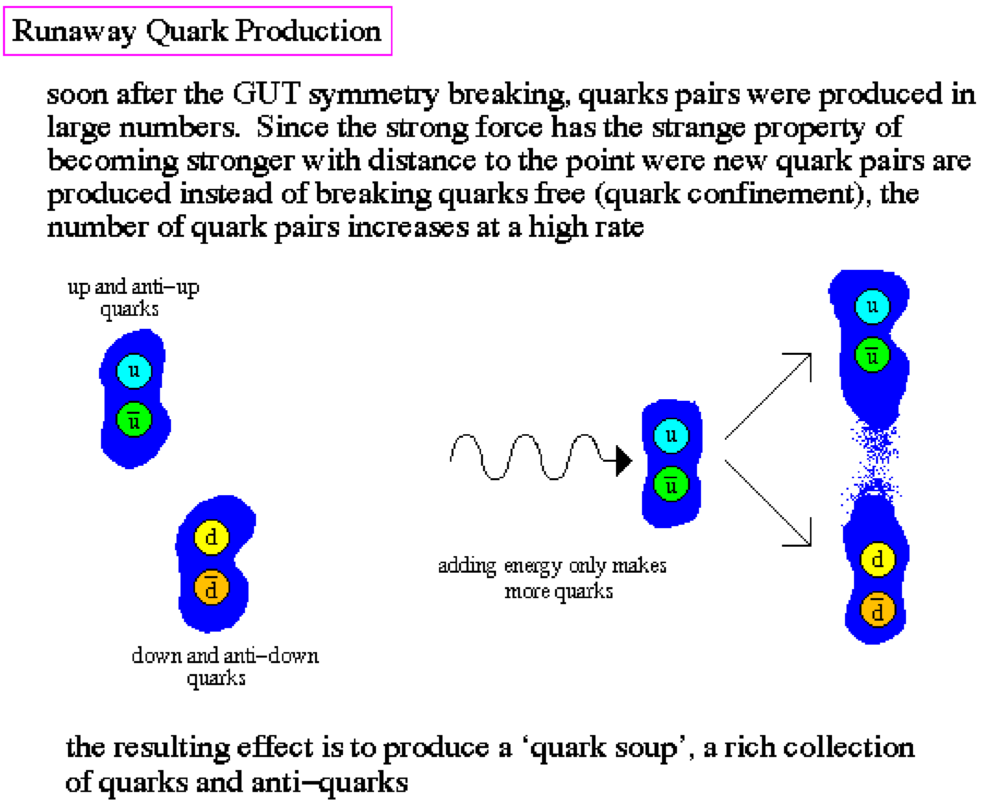



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Quarks and Leptons :

After GUT matter forms, the next phase is for GUT matter to decay into lepton and quark matter. Lepton matter will become our old friends the electron and neutrino (and their anti-particles). But quark matter is unusual because of the property of quark confinement.

Quarks can never be found in isolation because the strong force becomes stronger with distance. Any attempt to separate pairs or triplets of quarks requires large amounts of energy, which are used to produce new groups of quarks.



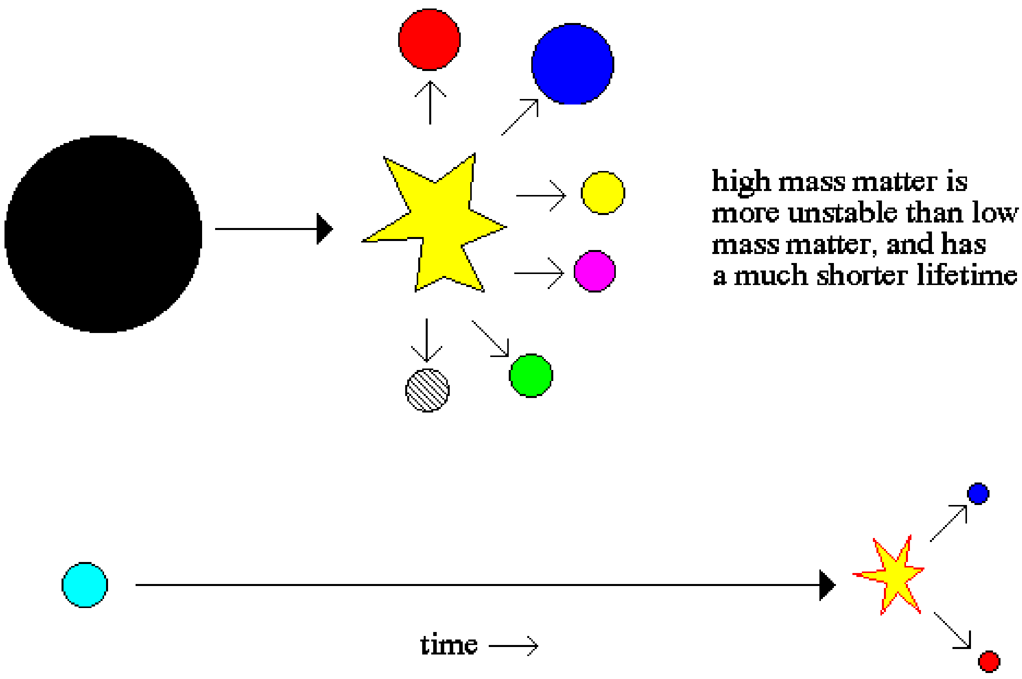

With so much energy available in the early Universe, the endresult is a runaway production of quark and anti-quark pairs. Trillions of times the amounts we currently see in the Universe. The resulting soup of quark pairs will eventually suffer massive annihilation of its matter and anti-matter sides as soon as the Universe expands and cools sufficiently for quark production to stop.

Notice that quark pairs are more stable than triplets, so that most of the quark production is done in pairs. Later, pairs will interact to form triplets, which are called baryons.

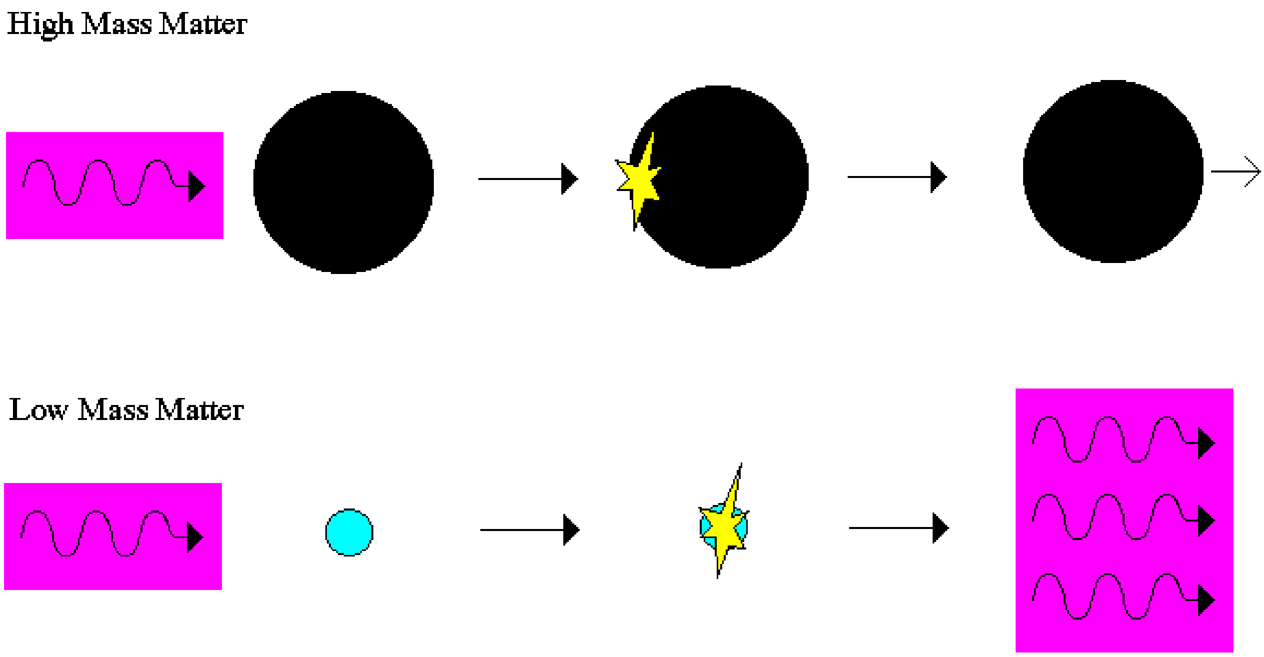
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Baryongenesis :

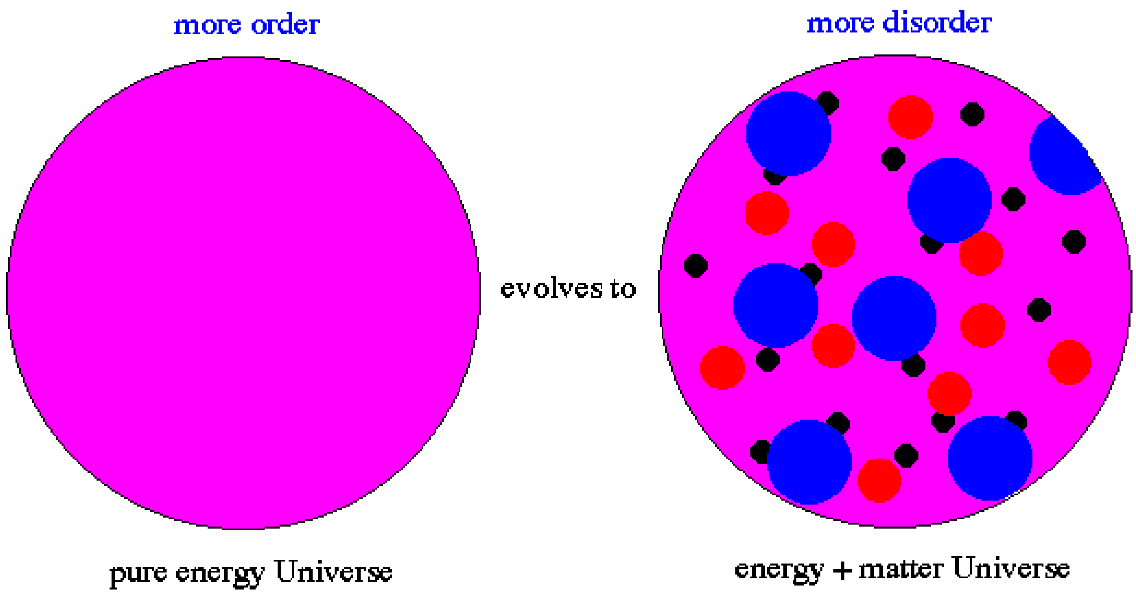
As the Universe cools a weak asymmetry in the direction towards matter becomes evident. Matter that is massive is unstable, particularly at the high temperature in the early Universe. Low mass matter is stable, but susceptible to destruction by high energy radiation (photons).




As the volume of the Universe increases, the lifetime of stable matter (its time between collisions with photons) increases. This also means that the time available for matter to interact with matter also increases.

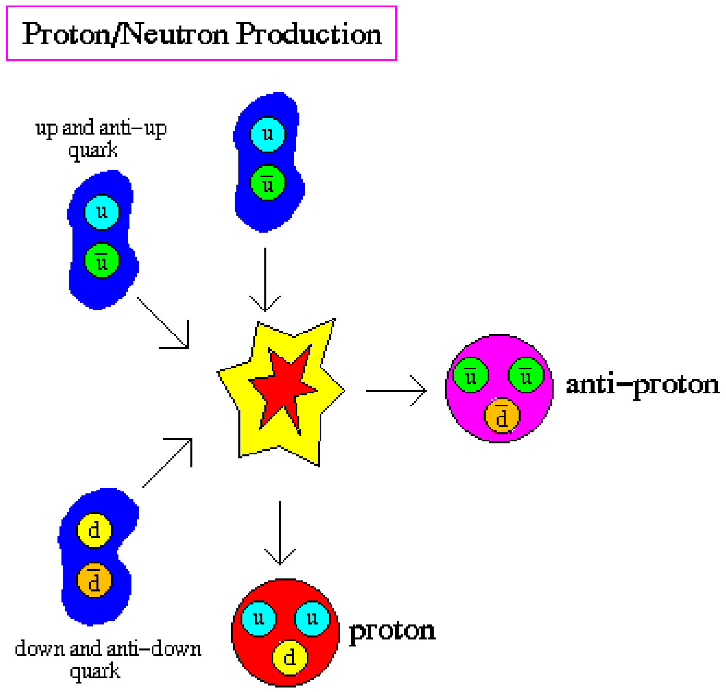



The Universe evolves from a pure, energy dominated domain to a more disordered, matter dominated domain, i.e. entropy marches on.




The last two stages of matter construction is the combining of three quark groups into baryons (protons and neutrons), then the collection of electrons by proton/neutron atomic nuclei to form atoms. The construction of baryons is called baryongenesis.

Baryongenesis begins around 1 second after the Big Bang. The equilibrium process at work is the balance between the strong force binding quarks into protons and neutrons versus the splitting of quark pairs into new quark pairs. When the temperature of the Universe drops to the point that there is not enough energy to form new quarks, the current quarks are able to link into stable triplets.




As all the anti-particles annihilate by colliding with their matter counterparts (leaving the small percentage of matter particles, see next lecture) leaving the remaining particles in the Universe to be photons, electrons, protons and neutrons. All quark pairs have reformed into baryons (protons and neutrons). Only around exotic objects, like black holes, do we find any anti-matter or mesons (quark pairs) or any of the other strange matter that was once found throughout the early Universe.

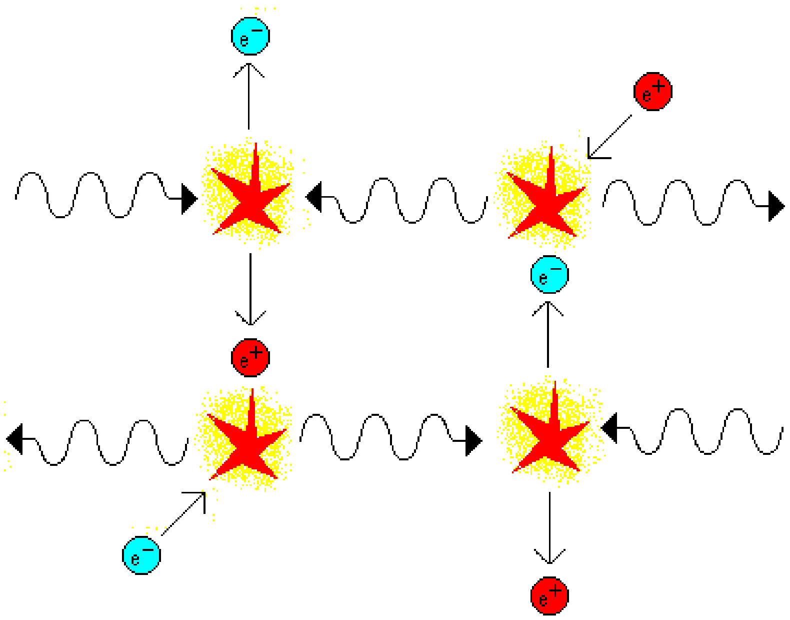
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Matter versus Anti-Matter :

Soon after the second symmetry breaking (the GUT era), there is still lots of energy available to produce matter by pair production, rather than quark confinement. However, the densities are so high that every matter and anti-matter particle produced is soon destroyed by collisions with other particles, in a cycle of equilibrium.

Particle Equilibrum

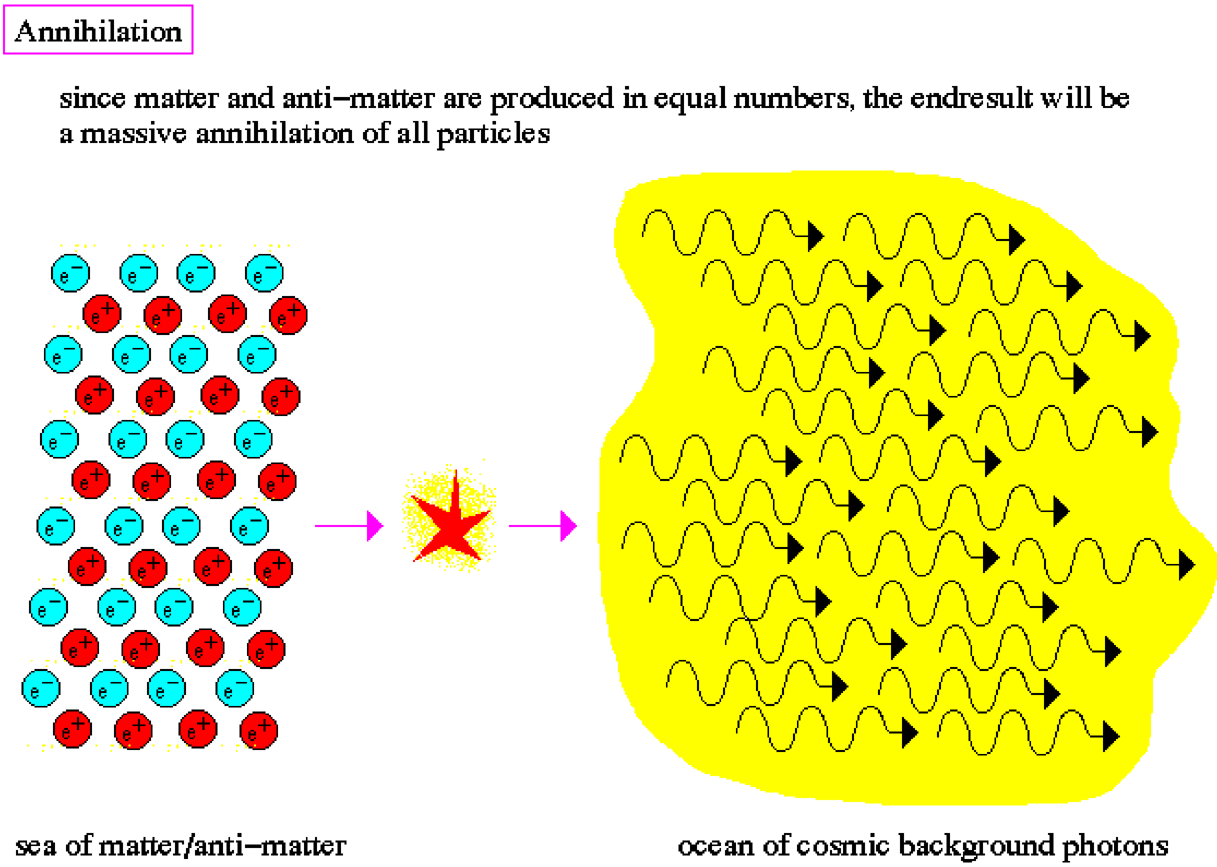
a state of particle equilibrium exists when the number of particle creations exactly matches the number of annihilations. Usually this is because there is no time for matter to decay or combine into new forms before a collision with an anti-particle




Notice that an equilibrum process keeps the number of matter and anti-matter particles equal.

Note that this process (and quark confinement) produces an equal number of matter and anti-matter particles, and that any particular time, if the process of pair production or quark confinement were to stop, then all matter and anti-matter would eventual collide and the Universe will be composed only of photons. In other words, since there are equal numbers of matter and anti-matter particles created by pair production, then why is the Universe made mostly of matter? Anti-matter is extremely rare at the present time, yet matter is very abundant.

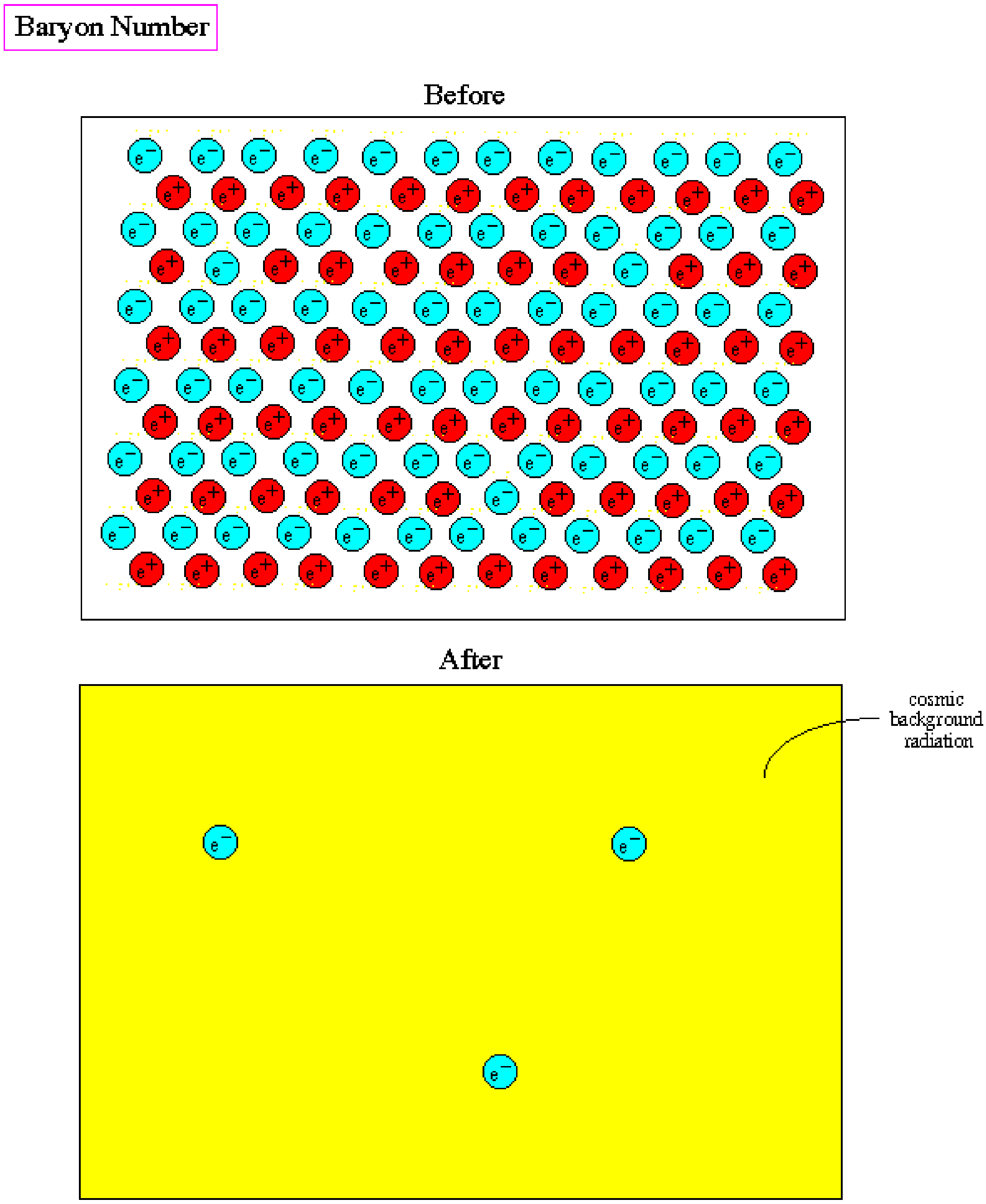
This asymmetry is called the matter/anti-matter puzzle. Why if particles are created symmetrically as matter and anti-matter does matter dominate the Universe today. In theory, all the matter and anti-matter should have canceled out and the Universe should be a ocean of photons.




It is not the case that the Universe is only filled with photons (look around the room). And it is not the case that 1/2 the Universe is matter and the other half is anti-matter (there would be alot of explosions).

Therefore, some mechanism produced more matter particle than anti-matter particles. How strong was this asymmetry? We can't go back in time and count the number of matter/anti-matter pairs, but we can count the number of cosmic background photons that remain after the annihilations. That counting yields a value of 1 matter particle for every $10^{10}$ photons, which means the asymmetry between matter and anti-matter was only 1 part in 10,000,000,000.

This means that for every 10,000,000,000 anti-matter particles there are 10,000,000,001 matter particles, an asymmetry of 1 particle out of 10 billion. And the endresult is that every 10 billion matter/anti-matter pairs annihilated each other leaving behind 1 matter particle and 10 billion photons that make up the cosmic background radiation, the echo of the Big Bang we measure today. This ratio of matter to photons is called the baryon number.




Even though the baryon number is extremely small ($10^{-10}$) why isn't it zero? In Nature, there are only three natural numbers, 0, 1 and infinity. All other numbers require explanation. What caused the asymmetry of even one extra matter particle for every 10 billion matter/anti-matter pairs?

One answer is that the asymmetry occurs because the Universe is out of equilibrium. This is clearly true because the Universe is expanding, and a dynamic thing is out of equilibrium (only static things are stable). And there are particular points in the history of the Universe when the system is out of equilibrium, the symmetry breaking moments. Notice also that during the inflation era, any asymmetries in the microscopic world would be magnified into the macroscopic world. One such quantum asymmetry is CP violation.

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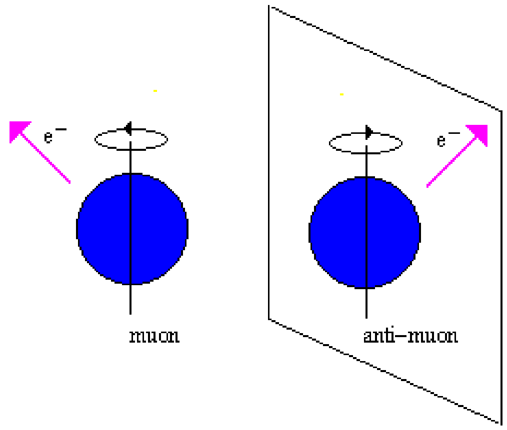
CP Violation:

As the Universe expands and cools and the process of creation and annihilation of matter/anti-matter pairs slows down. Soon matter and anti-matter has time to undergo other nuclear processes, such as nuclear decay. Many exotic particles, massive bosons or mesons, can undergo decay into smaller particles. If the Universe is out of equilibrium, then the decay process, fixed by the emergent laws of Nature, can become out of balance if there exists some asymmetry in the rules of particle interactions. This would result in the

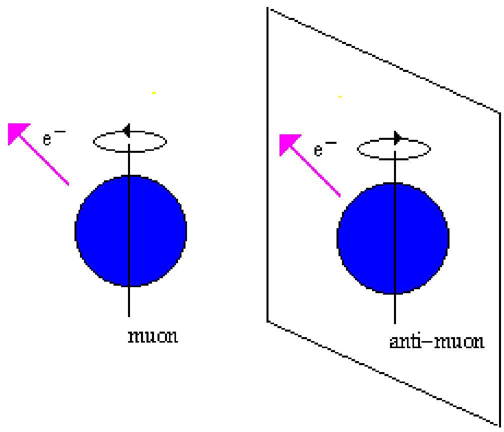
production of extra matter particles, rather than equal numbers of matter and anti-matter.

In the quantum world, there are large numbers of symmetric relationships. For example, there is the symmetry between matter and anti-matter. For every matter particle, there is a corresponding anti-matter particle of opposite charge. In the 1960's, it was found that some types of particles did not conserve left or right-handedness during their decay into other particles. This property, called parity, was found to be broken in a small number of interactions at the same time the charge symmetry was also broken and became known as CP violation.

Parity, for elementary particles, can be defined with respect to the direction in which they emit decay particles. A muon will typically emit an electron to the right. If the parity is reversed, then the muon should emit the electron to the left, the mirror image.

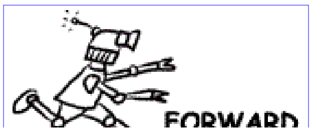



One time out of a thousand, an anti–muon will decay to the right, a violation of the charge–parity or CP rule.



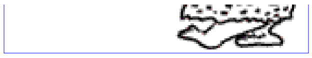

The symmetry is restored when particle interactions are considered under the global CPT rule (charge - parity - time reversal), which states that that a particle and its anti-particle may be different, but will behave the same in a mirror-reflected, time-reversed study. During the inflation era, the rapid expansion of spacetime would have thrown the T in CPT symmetry out of balance, and the CP violation would have produced a small asymmetry in the baryon number.

This is another example of how quantum effects can be magnified to produce large consequences in the macroscopic world.



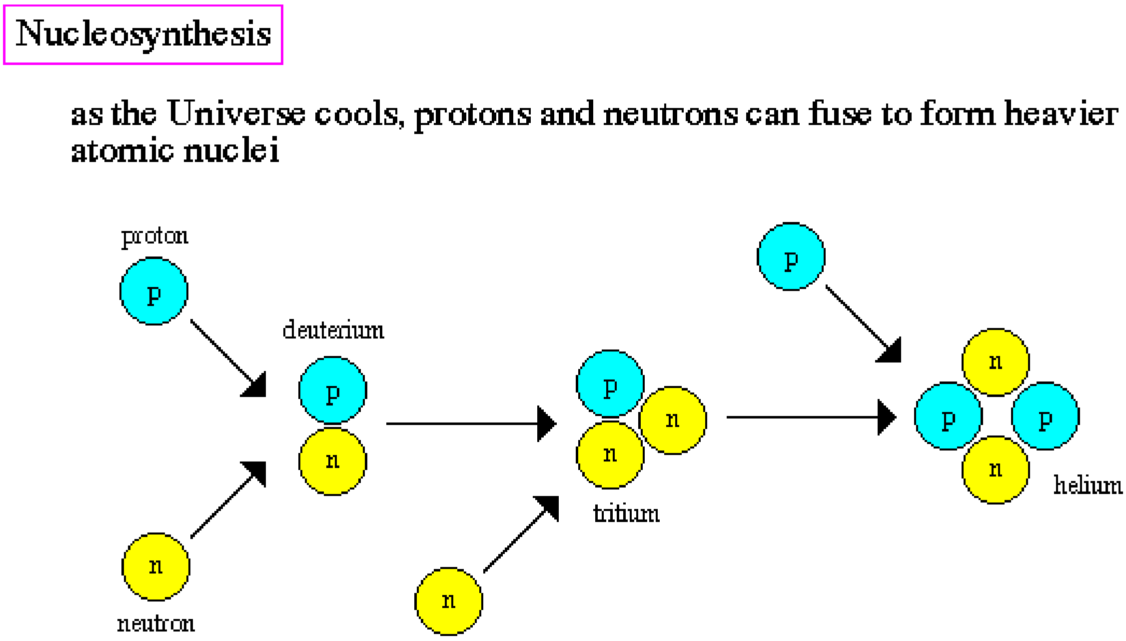




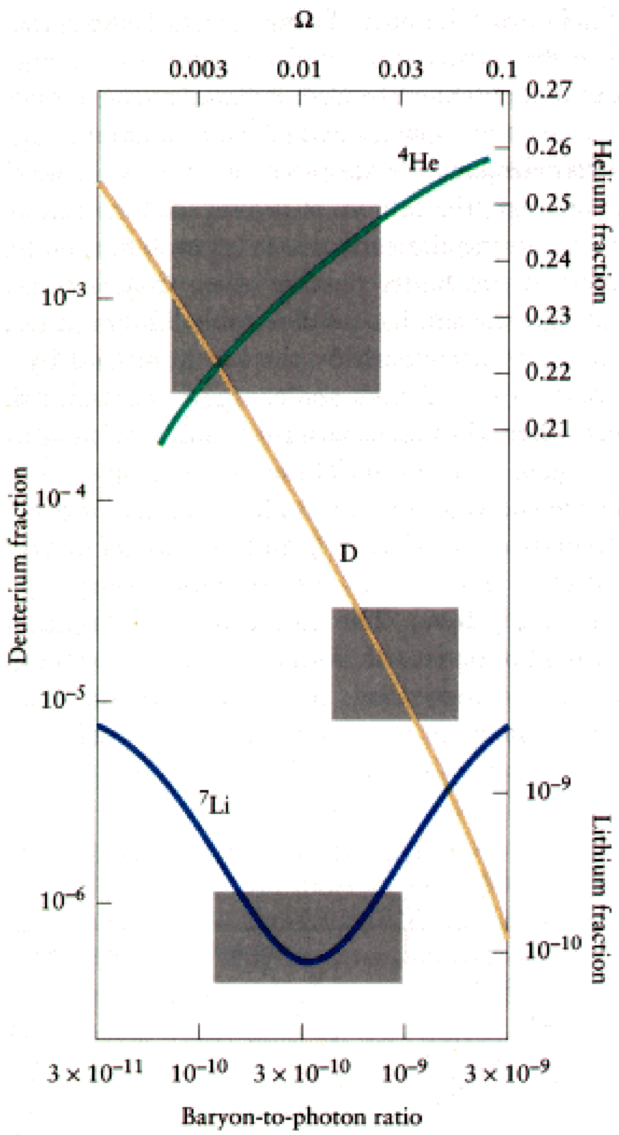


Nucleosynthesis:

The Universe is now 1 minute old, and all the anti-matter has been destroyed by annihilation with matter. The leftover matter is in the form of electrons, protons and neutrons. As the temperature continues to drop, protons and neutrons can undergo fusion to form heavier atomic nuclei. This process is called nucleosynthesis.

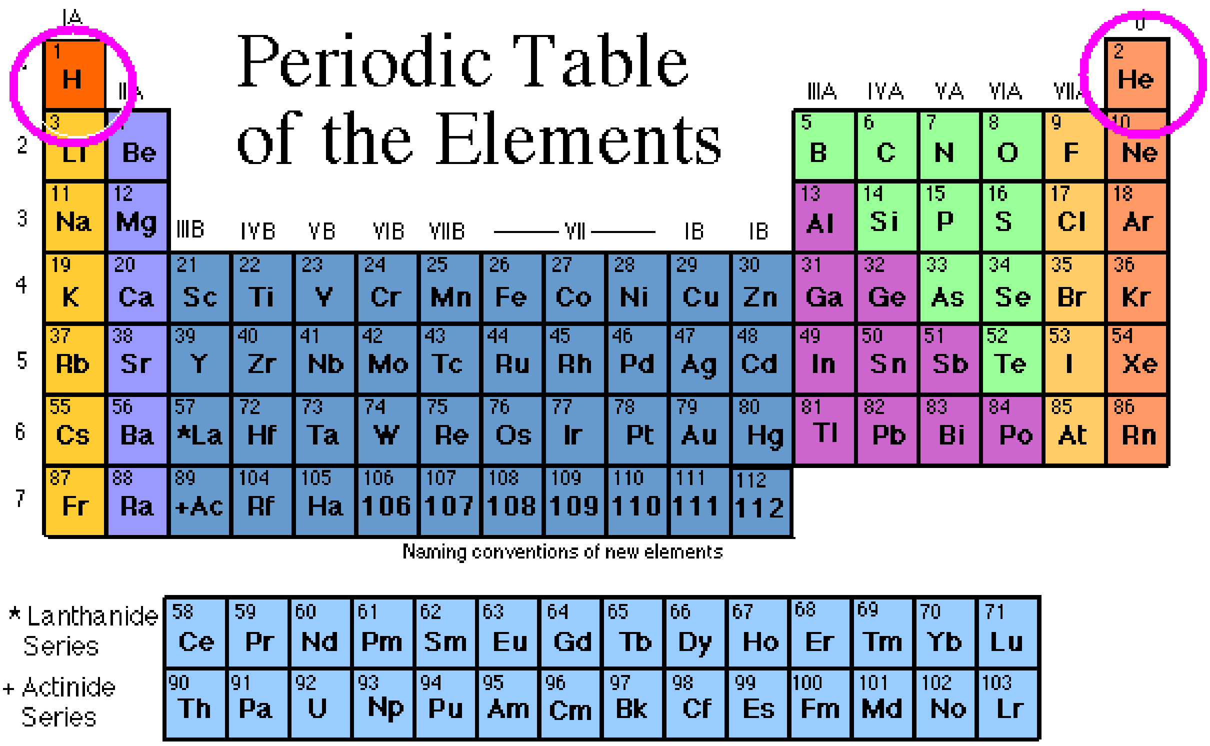



Its harder and harder to make nuclei with higher masses. So the most common substance in the Universe is hydrogen (one proton), followed by helium, lithium, beryllium and boron (the first elements on the periodic table). Isotopes are formed, such as deuterium and tritium, but these elements are unstable and decay into free protons and neutrons.




Note that this above diagram refers to the density parameter, Omega, of baryons, which is close to 0.1. However, much of the Universe is in the form of dark matter (see later lecture).

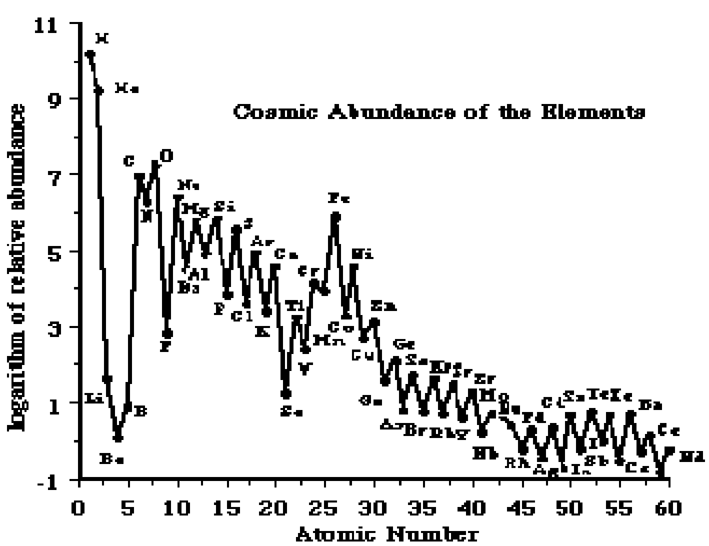
A key point is that the ratio of hydrogen to helium is extremely sensitive to the density of matter in the Universe (the parameter that determines if the Universe is open, flat or closed). The higher the density, the more helium produced during the nucleosynthesis era. The current measurements indicate that 75% of the mass of the Universe is in the form of hydrogen, 24% in the form of helium and the remaining 1% in the rest of the periodic table (note that your body is made mostly of these `trace' elements). Note that since helium is 4 times the mass of hydrogen, the number of hydrogen atoms is 90% and the number of helium atoms is 9% of the total number of atoms in the Universe.



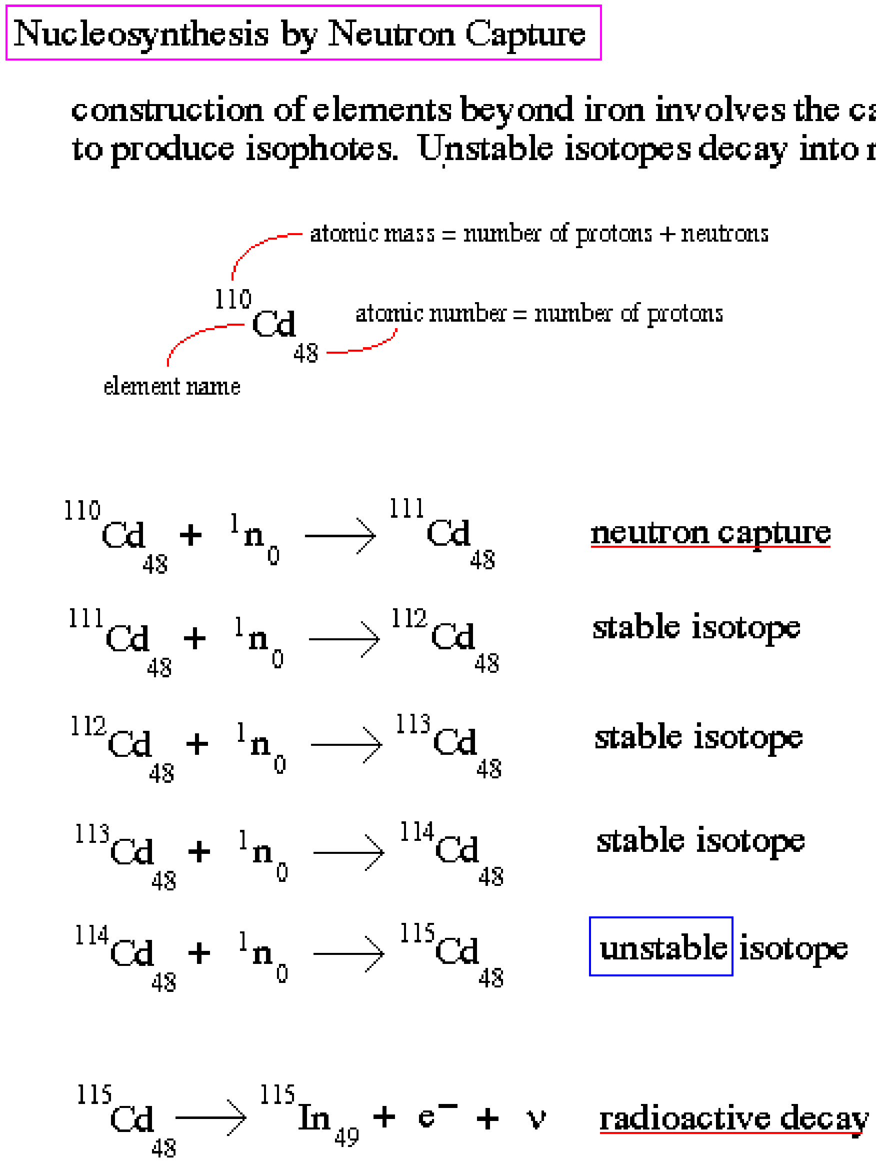

There are over 100 naturally occurring elements in the Universe and classification makes up the periodic table. The very lightest elements are made in the early Universe. The elements between boron and iron (atomic number 26) are made in the cores of stars by thermonuclear fusion, the power source for all stars.

The fusion process produces energy, which keeps the temperature of a stellar core high to keep the reaction rates high. The fusing of new elements is balanced by the destruction of nuclei by high energy gamma-rays. Gamma-rays in a stellar core are capable of disrupting nuclei, emitting free protons and neutrons. If the reaction rates are high, then a net flux of energy is produced.

Fusion of elements with atomic numbers (the number of protons) greater than 26 uses up more energy than is produced by the reaction. Thus, elements heavier than iron cannot be fuel sources in stars. And, likewise, elements heavier than iron are not produced in stars, so what is their origin?.



The construction of elements heavier than involves nucleosynthesis by neutron capture. A nuclei can capture or fuse with a neutron because the neutron is electrically neutral and, therefore, not repulsed like the proton. In everyday life, free neutrons are rare because they have short half-life's before they radioactively decay. Each neutron capture produces an isotope, some are stable, some are unstable. Unstable isotopes will decay by emitting a positron and a neutrino to make a new element.




Neutron capture can happen by two methods, the s and r-processes, where s and r stand for slow and rapid. The s-process happens in the inert carbon core of a star, the slow capture of neutrons. The s-process works as long as the decay time for unstable isotopes is longer than the capture time. Up to the element bismuth (atomic number 83), the s-process works, but above this point the more massive nuclei that can be built from bismuth are unstable.

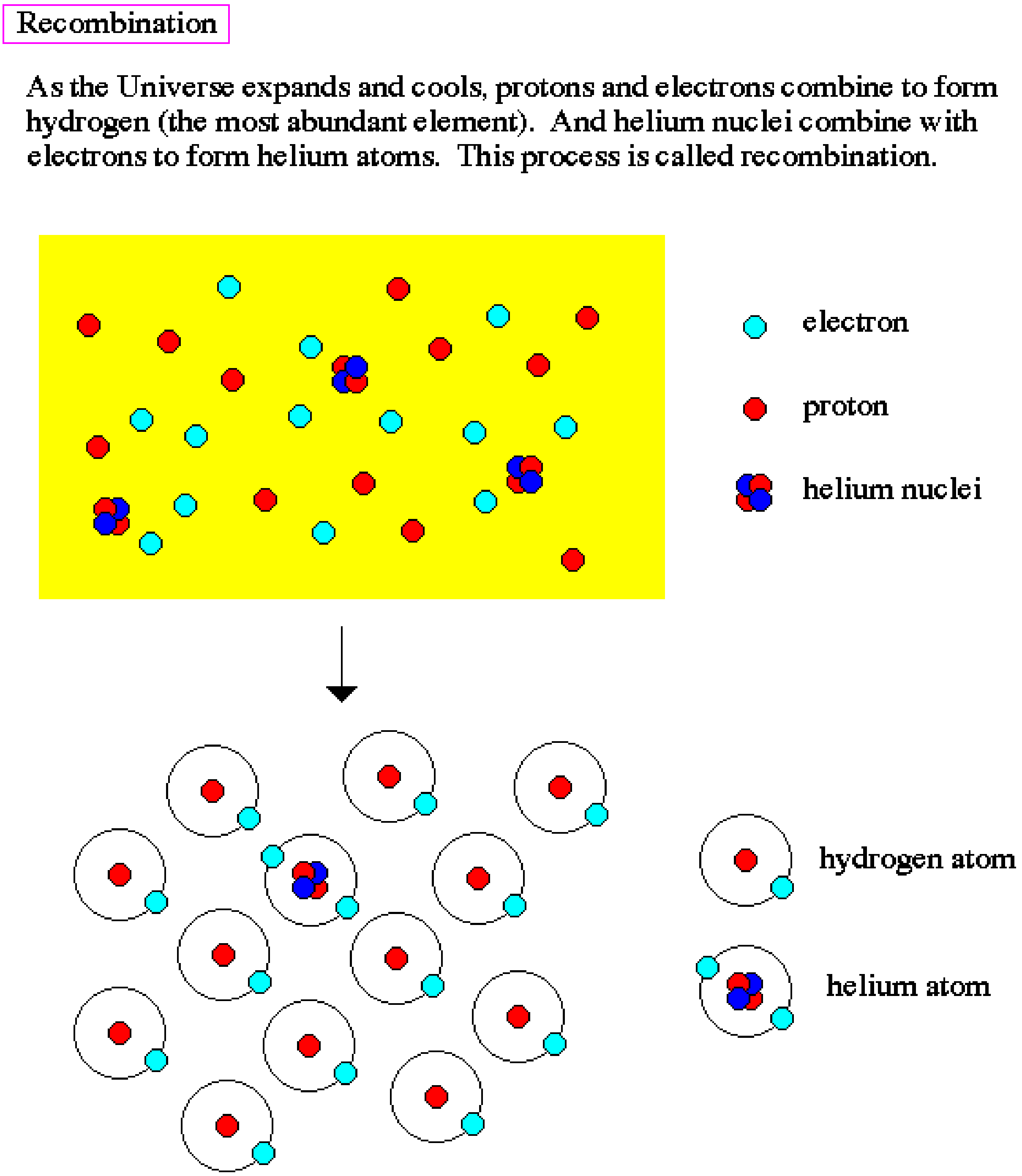
The second process, the r-process, is what is used to produce very heavy, neutron rich nuclei. Here the capture of neutrons happens in such a dense environment that the unstable isotopes do not have time to decay. The high density of neutrons needed is only

found during a supernova explosion and, thus, all the heavy elements in the Universe (radium, uranium and plutonium) are produced this way. The supernova explosion also has the side benefit of propelling the new created elements into space to seed molecular clouds which will form new stars and solar systems.

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Ionization:

The last stage in matter production is when the Universe cools sufficiently for electrons to combine with the proton/neutron nuclei and form atoms. Constant impacts by photons knock electrons off of atoms which is called ionization. Lower temperatures mean photons with less energy and fewer collisions. Thus, atoms become stable at about 15 minutes after the Big Bang.



These atoms are now free to bond together to form simple compounds, molecules, etc. And these are the building blocks for galaxies and stars.

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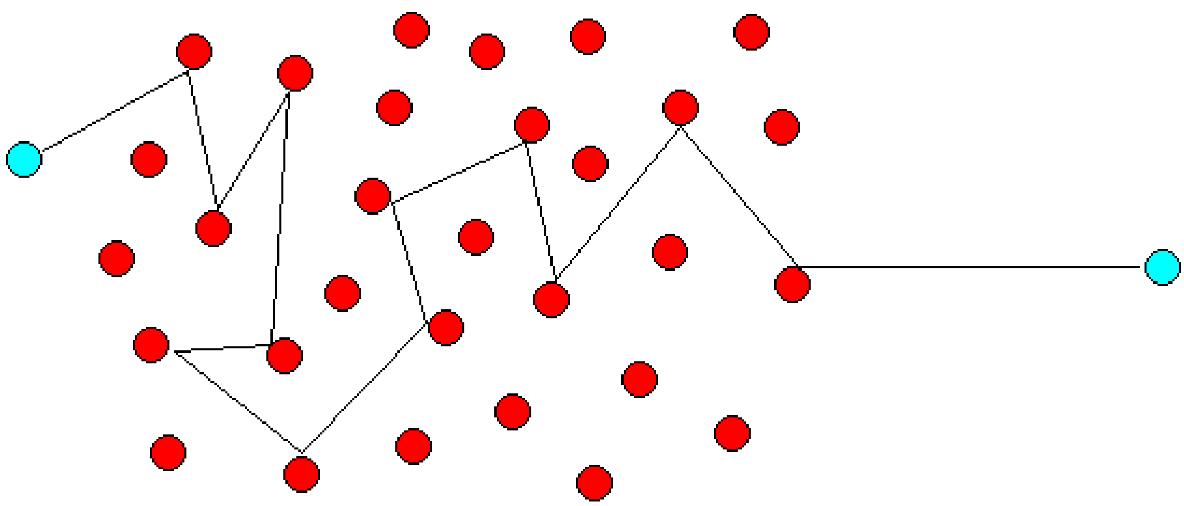
Radiation/Matter Dominance :

Even after the annihilation of anti-matter and the formation of protons, neutrons and electrons, the Universe is still a violent and extremely active environment. The photons created by the matter/anti-matter annihilation epoch exist in vast numbers and have energies at the x-ray level.

Radiation, in the form of photons, and matter, in the form of protons, neutrons and electron, can interact by the process of scattering. Photons bounce off of elementary particles, much like billiard balls. The energy of the photons is transfered to the matter particles. The distance a photon can travel before hitting a matter particle is called the mean free path.

Mean Free Path

all particles, including photons, suffer from collisions with other particles such that their path through space is very short the higher the densities. This typical path length is called the mean free path.



the Universe is opaque at high densities (the mean free path of a photon is very short), as the density drops with time, the Universe becomes transparent (the mean free path of a photon becomes very large).

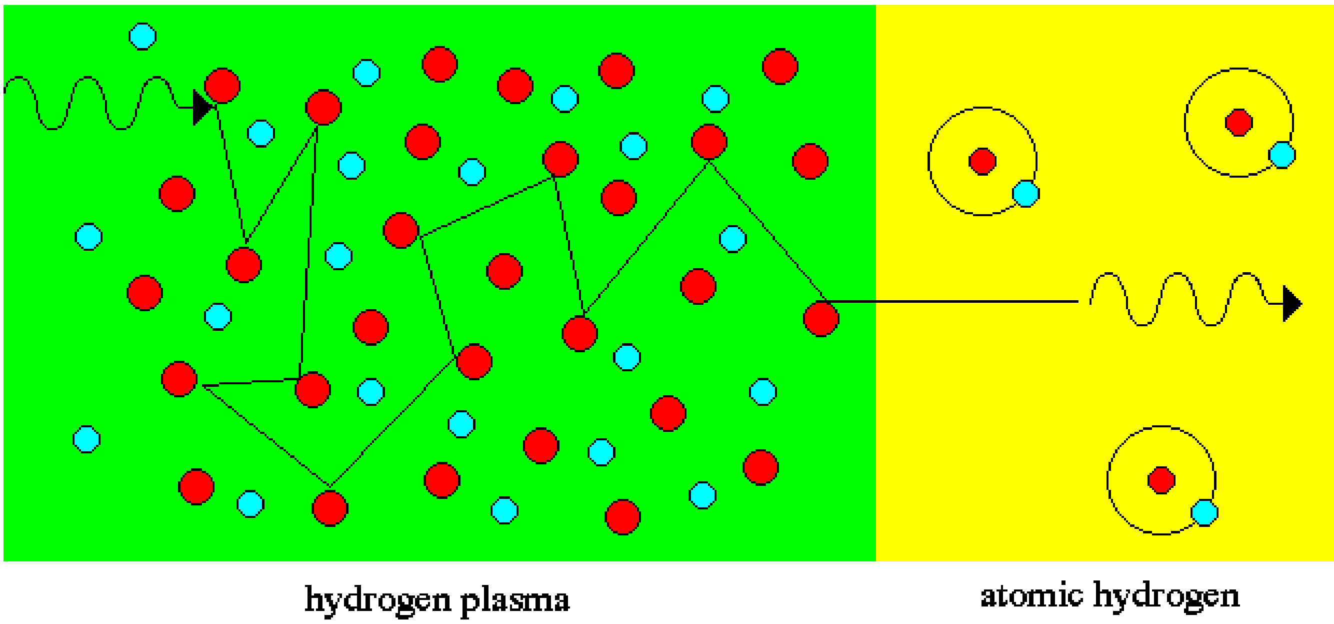
Since matter and photons were in constant contact, their temperatures were the same, a process called thermalization. Note also that the matter can not clump together by gravity. The impacts by photons keep the matter particles apart and smoothly distributed.

The density and the temperature for the Universe continues to drop as it expands. At some point about 15 minutes after the Big Bang, the temperature has dropped to the point where ionization no longer takes places. Neutral atoms can form, atomic nuclei surround by

electron clouds. The number of free particles drops by a large fraction (all the protons, neutrons and electron form atoms). And suddenly the photons are free to travel without collisions, this is called decoupling.

Last Scattering Epoch

As the Universe cooled, the free electrons and protons could finally bond togther to form hydrogen atoms. At the same time, the Universe went from a rich plasma to a gas of neutral hydrogen.



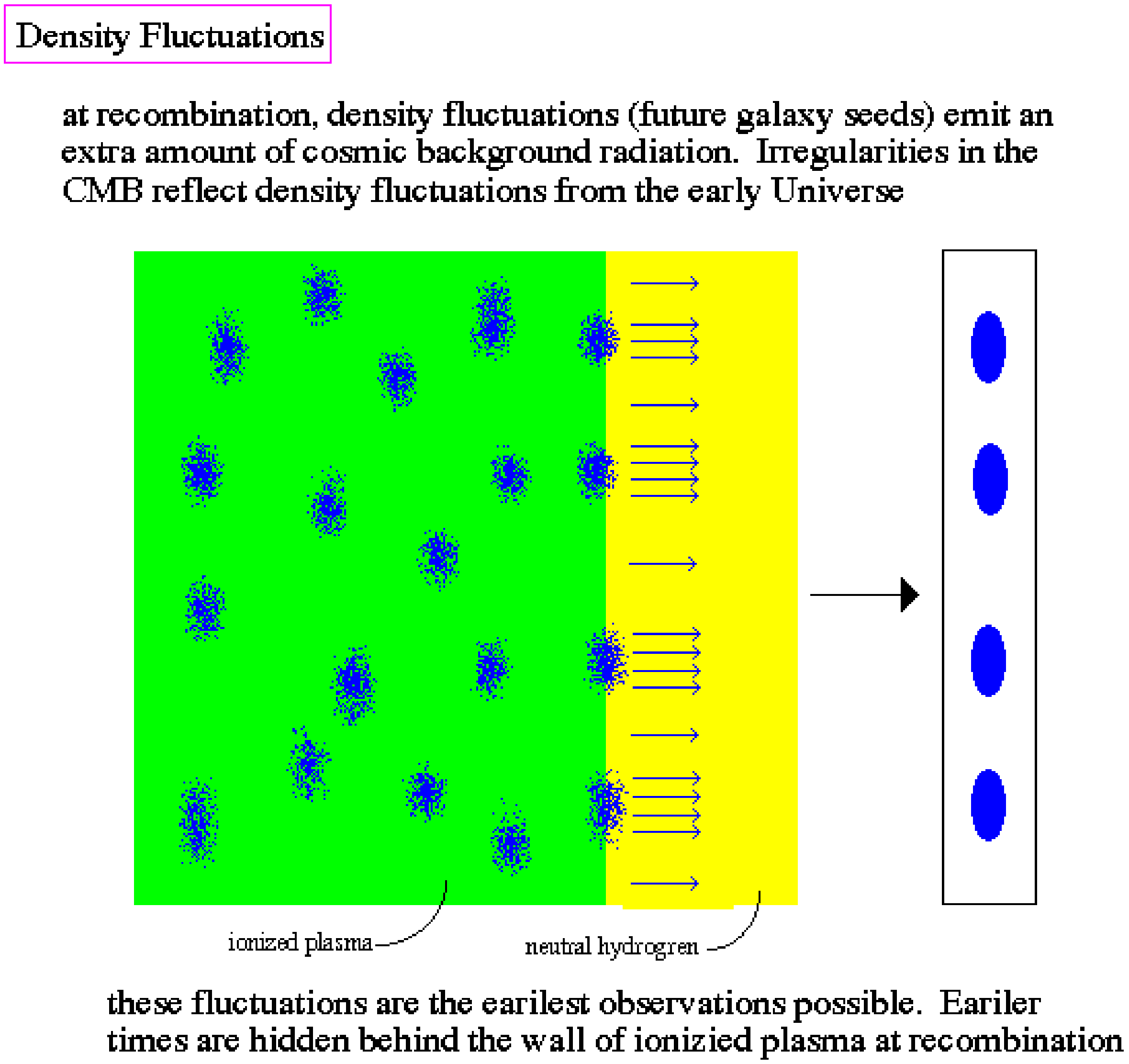

In a plasma, the mean free path of a photon is very short. In a gas of atomic hydrogen, the mean free path is very long, as long as the size of the Universe. Thus, the transition from the early plasma to atomic hydrogen is the epoch of last scattering, the point in time when the photons became free to travel without hindrance.

The Universe becomes transparent at this point. Before this epoch, a photon couldn't travel more that a few inches before a collision. So an observers line-of-sight was only a few inches and the Universe was opaque, matter and radiation were coupled. This is the transition from the radiation era to the matter era.

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Density Fluctuations:

The time of neutral atom construction is called recombination, this is also the first epoch we can observe in the Universe. Before recombination, the Universe was too dense and opaque. After recombination, photons are free to travel through all of space. Thus, the limit to our observable Universe is back in time (outward in space) to the moment of recombination.



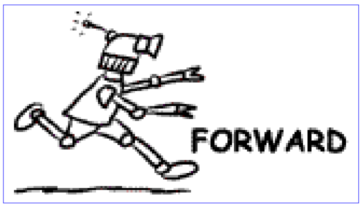

The time of recombination is also where the linked behavior between photons and matter decouples or breaks, and is also the last epoch where radiation traces the mass density. Photon/matter collisions become rare and the evolution of the Universe is dominated by the behavior of matter (i.e. gravity), so this time, and until today, is called the matter era.

Today, radiation in the form of photons have a very passive role in the evolution of the Universe. They only serve to illuminate matter in the far reaches of the Galaxy and other galaxies. Matter, on the other hand, is free to interact without being jousted by photons. Matter becomes the organizational element of the Universe, and its controlling force is gravity.

Notice that as the Universe ages it moves to more stable elements. High energy radiation (photons) are unstable in their interactions with matter. But, as matter condenses out of the cooling Universe, a more stable epoch is entered, one where the slow, gentle force of gravity dominates over the nuclear forces of earlier times.

Much of the hydrogen that was created at recombination was used up in the formation of galaxies, and converted into stars. There is very little reminant hydrogen between galaxies, the so-called intergalactic medium, except in clusters of galaxies. Clusters of galaxies frequently have a hot hydrogen gas surrounding the core, this is leftover gas from

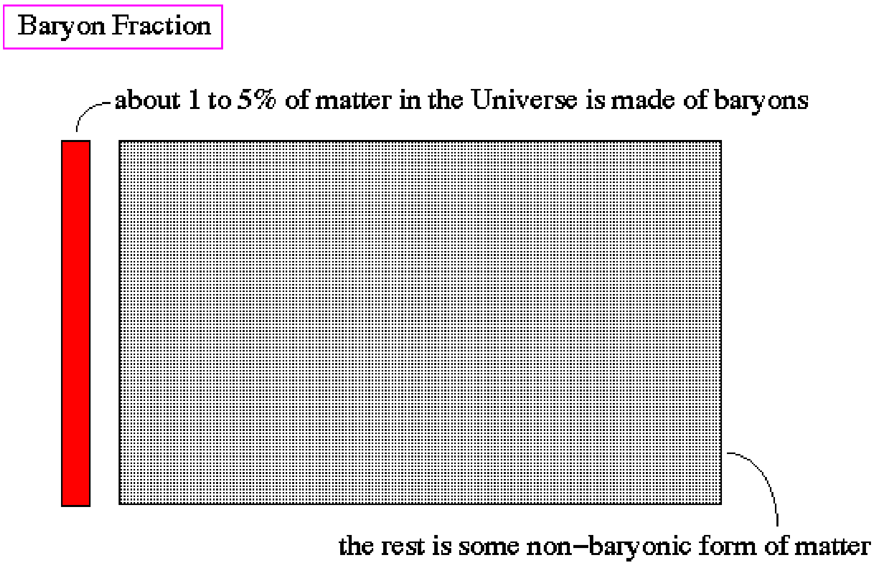
the formation of the cluster galaxies that has been heated by the motions of the cluster members.






Baryon Fraction:

The amount of hydrogen in the Universe today, either in stars and galaxies, or hot gas between galaxies, is called the baryon fraction. The current measurements indicate that the baryon fraction is about 3% (0.03) the value of closure for the Universe (the critical density). Remember the value from the abundance of light elements is 10% (0.10) the closure value.




The most immediate result here is that the mass density of the Universe appears to be much less than the closure value, i.e. we live in an open Universe. However, the inflation model demands that we live in a Universe with exactly the critical density, Omega of 1. This can only be true if about 90% of the mass of the Universe is not in baryons.

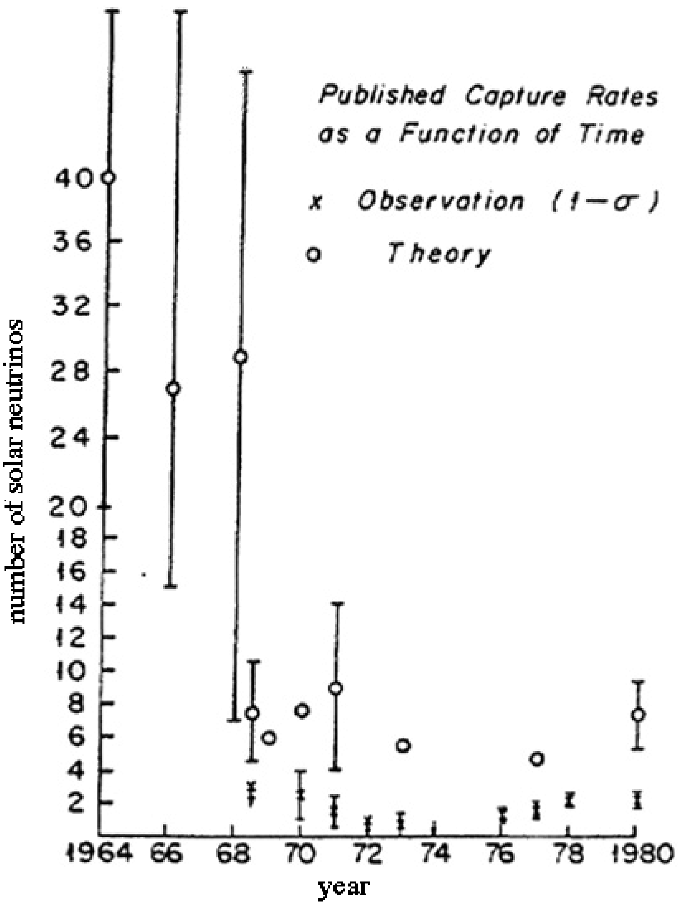
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Neutrinos :

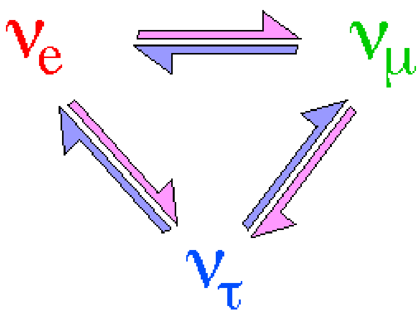
There are two types of leptons, the electron and the neutrino. The neutrino is a strange particle, not discovered directly, but by inference from the decay of other particles by Wolfgang Pauli in 1930. It has no charge and a very small mass. It interacts with other particles only through the weak force (i.e. it is immune to the strong and electromagnetic forces). The weak force is so weak, that a neutrino can pass through several Earth's of lead with only a 50/50 chance of interacting with an atom, i.e. they are effectively transparent to matter.

The weakly interacting nature of neutrinos makes them very difficult to detect, and therefore measure, in experiments. Plus, the only sources of large amounts of neutrinos are high energy events such as supernova, relics from the early Universe and nuclear power plants. However, they are extremely important to our understanding of nuclear reactions since pratically every fusion reaction produces a neutrino. In fact, a majority of the energy produced by stars and supernova are carried away in the form of neutrinos (the Sun produces 100 trillion trillion trillion neutrinos every second).

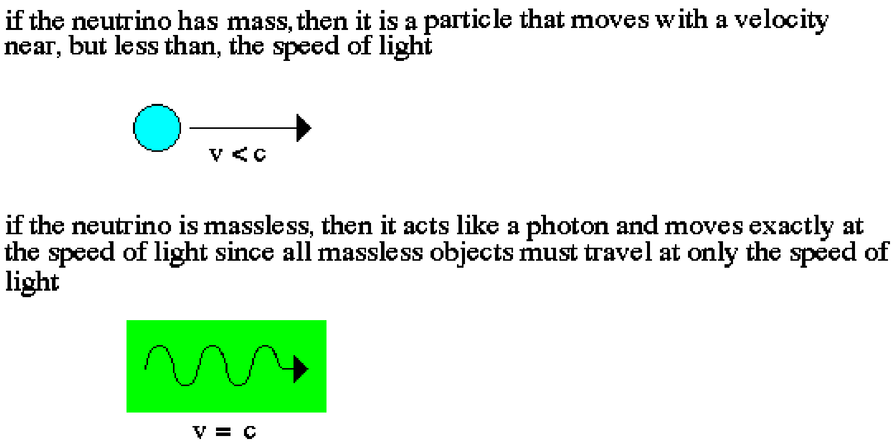
Detecting neutrinos from the Sun was an obvious first experiment to measure neutrinos. The pioneering experiment was Ray Davis's 600 tonne chlorine tank (actually dry cleaning fluid) in the Homestake mine, South Dakota. His experiment, begun in 1967, found evidence for only one third of the expected number of neutrino events. A light water Cherenkov experiment at Kamioka, Japan, upgraded to detect solar netrinos in 1986, finds one half of the expected events for the part of the solar neutrino spectrum for which they are sensitive. Two recent gallium detectors (SAGE and GALLEX), which have lower energy thresholds, find about 60-70% of the expected rate.




The clear trend is that the measured flux is found to be dramatically less than is possible for our present understanding of the reaction processes in stars. There are two possible answers to this problem: 1) The structure and constitution of stars, and hence the reaction mechanisms are not correctly understood (this would be a real blow for models that have otherwise been very successful), or 2) something happens to the neutrinos in transit to earth; in particular, they might change into another type of neutrino, call oscillation (this idea is not as crazy as it sounds, as a similar phenomenon is well known to occur with the meson particles). An important consequence to oscillation is that the neutrino must have mass (unlike the photon which has zero mass).




By the late 1990s, the oscillation hypothesis is shown to be correct. In addition, analysis of the neutrino events from the supernova 1987A indicates that the neutrinos traveled at slightly less than the speed of light. This is an important result since the neutrino is so light that it was unclear if its mass was very small or exact zero. Zero mass particles (like the photon) must travel exactly the speed of light (no faster, no slower). But objects with mass must travel at less than the speed of light as stated by special relativity.




Since neutrino's interact very weakly, they are the first particles to decouple from other particles, at about 1 sec after the Big Bang. The early Universe is so dense that even neutrinos are trapped in their interactions. But as the Universe expands, its density drops to the point where the neutrinos are free to travel. This happens when the rate at which neutrinos are absorbed and emitted (the weak interaction rate) becomes slower than the expansion rate of the Universe. At this point the Universe expands faster than the neutrinos are absorbed and they take off into space (the expanding space).

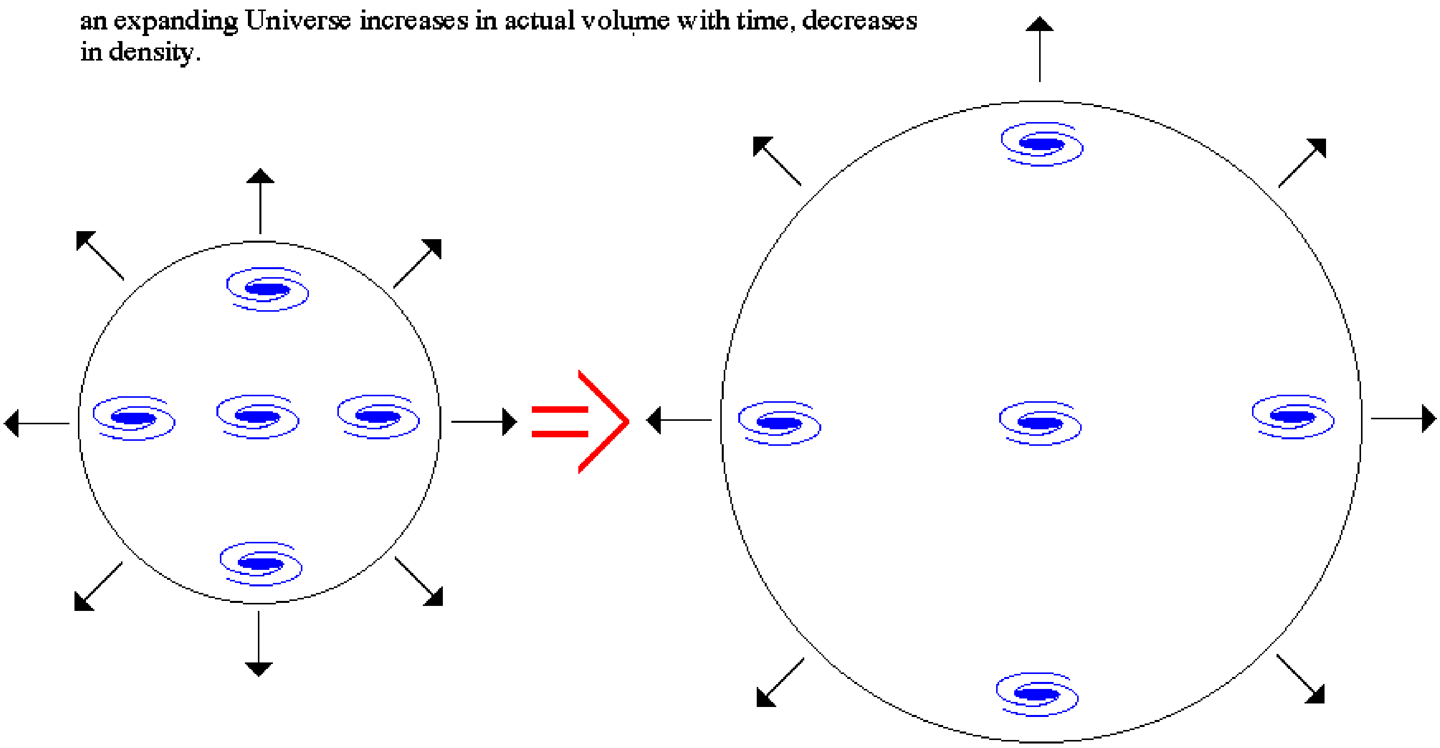
Now that neutrinos have been found to have mass, they also are important to our cosmology as a component of the cosmic density parameter. Even though each individual neutrino is much less massive than an electron, trillions of them are produced for every electron in the early Universe. Thus, neutrinos must make up some fraction of the non-baryonic matter in the Universe (although not alot of it, see lecture on the large scale structure of the Universe).

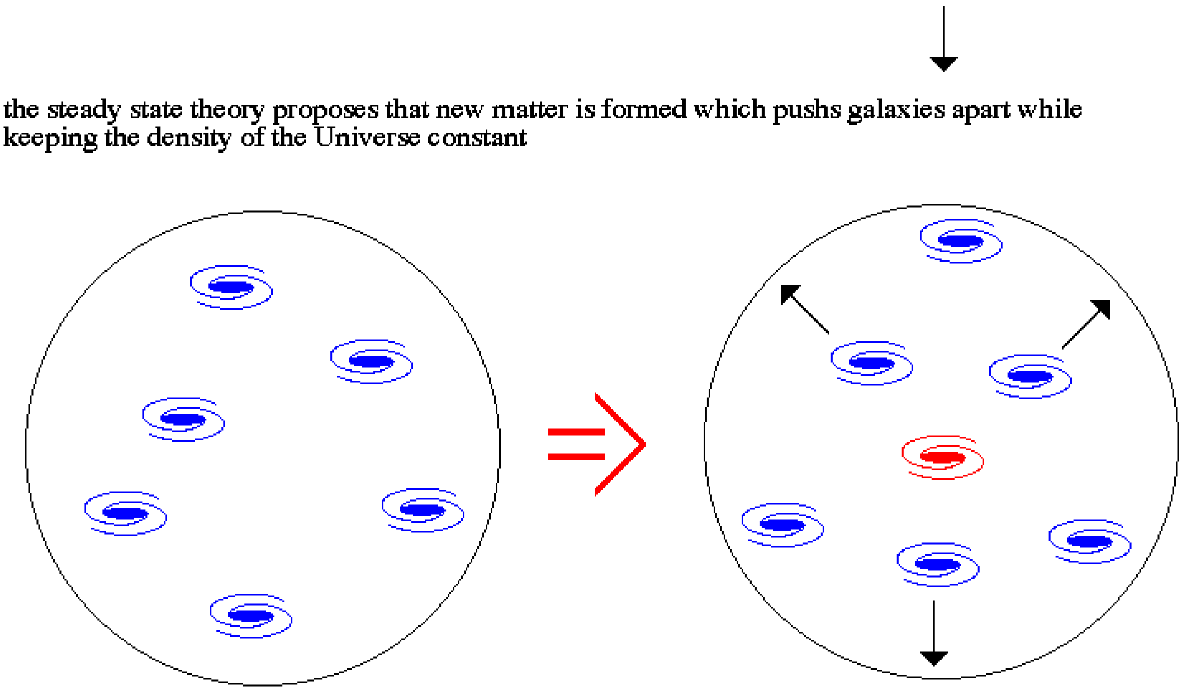
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Cosmic Background Radiation :

One of the foremost cosmological discoveries was the detection of the cosmic background radiation. The discovery of an expanding Universe by Hubble was critical to our understanding of the origin of the Universe, known as the Big Bang. However, a dynamic Universe can also be explained by the steady state theory.

The steady state theory avoids the idea of Creation by assuming that the Universe has been expanding forever. Since this would mean that the density of the Universe would get smaller and smaller with each passing year (and surveys of galaxies out to distant volumes shows this is not the case), the steady-state theory requires that new matter be produced to keep the density constant.





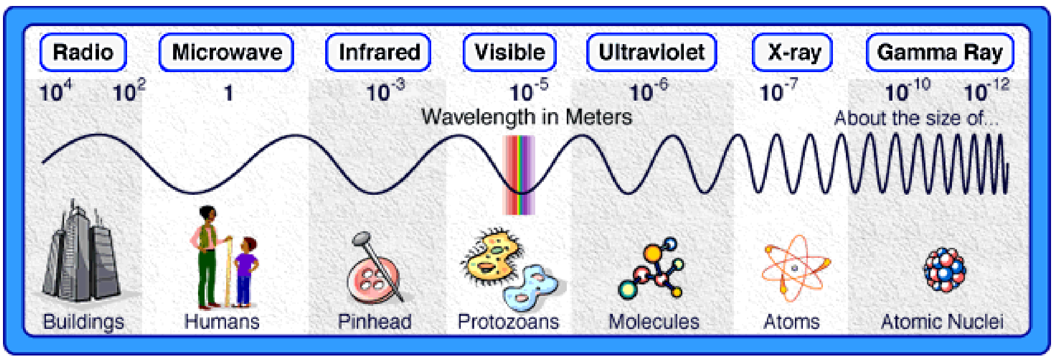

The creation of new matter would voilate the conservation of matter princple, but the amount needed would only be one atom per cubic meter per 100 years to match the expansion rate given by Hubble's constant.

The discovery of the cosmic microwave background (CMB) confirmed the explosive nature to the origin of our Universe. For every matter particle in the Universe there are 10 billion more photons. This is the baryon number that reflects the asymmetry between matter and anti-matter in the early Universe. Looking around the Universe its obvious that there is a great deal of matter. By the same token, there are even many, many more photons from the initial annihilation of matter and anti-matter.

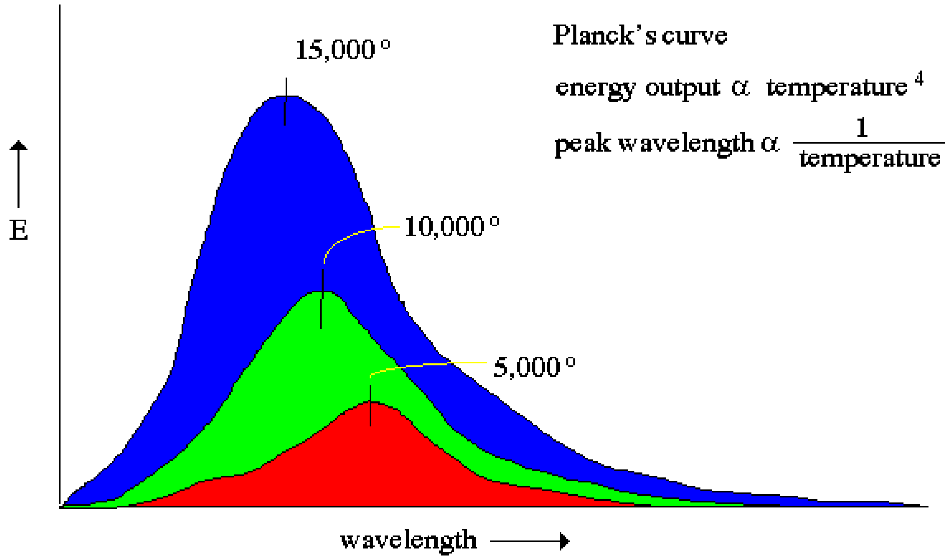
Most of the photons that you see with your naked eye at night come from the centers of stars. Photons created by nuclear fusion at the cores of stars then scatter their way out from a star's center to its surface, to shine in the night sky. But these photons only make up a very small fraction of the total number of photons in the Universe. Most photons in the Universe are cosmic background radiation, invisible to the eye.

Cosmic background photons have their origin at the matter/anti-matter annihilation era and, thus, were formed as gamma-rays. But, since then, they have found themselves scattering off particles during the radiation era. At recombination, these cosmic background photons escaped from the interaction with matter to travel freely through the Universe.

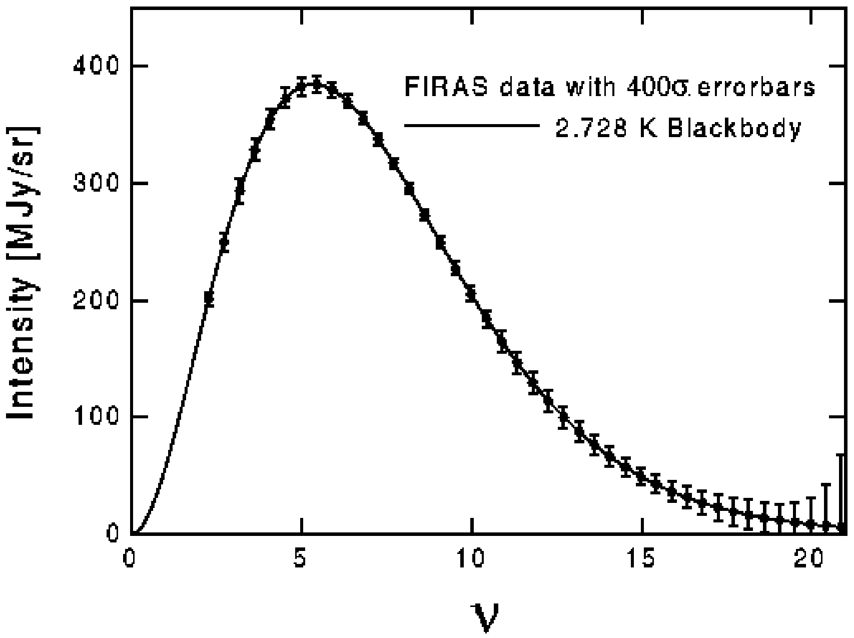
As the Universe continued to expanded over the last 15 billion years, these cosmic background photons also `expanded', meaning their wavelengths increased. The original gamma-ray energies of cosmic background photons has since cooled to microwave wavelengths. Thus, this microwave radiation that we see today is an `echo' of the Big Bang.




The discovery of the cosmic microwave background (CMB) in the early 1960's was powerful confirmation of the Big Bang theory. Since the time of recombination, cosmic background photons have been free to travel uninhibited by interactions with matter. Thus, we expect their distribution of energy to be a perfect blackbody curve. A blackbody is the curve expected from a thermal distribution of photons, in this case from the thermalization era before recombination.




Today, based on space-based observations because the microwave region of the spectrum is blocked by the Earth's atmosphere, we have an accurate map of the CMB's energy curve. The peak of the curve represents the mean temperature of the CMB, 2.7 degrees about absolute zero, the temperature the Universe has dropped to 15 billion years after the Big Bang.




Where are the CMB photons at the moment? The answer is `all around you'. CMB photons fill the Universe, and this lecture hall, but their energies are so weak after 15 billion years that they are difficult to detect without very sensitive microwave antennas.

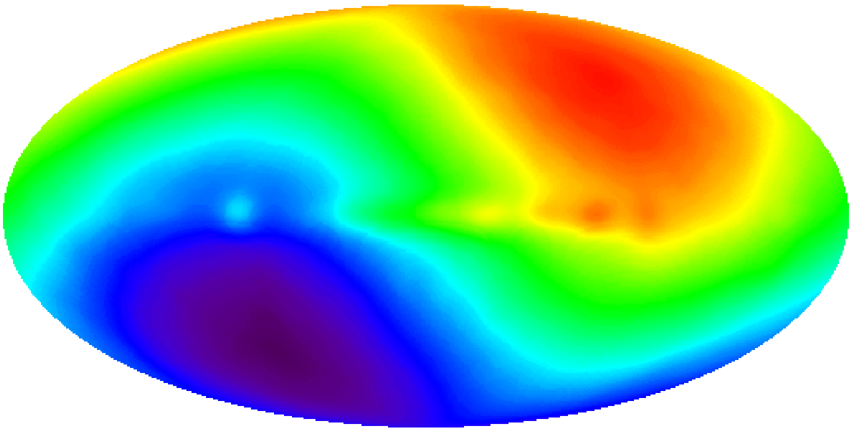
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CMB Fluctuations :

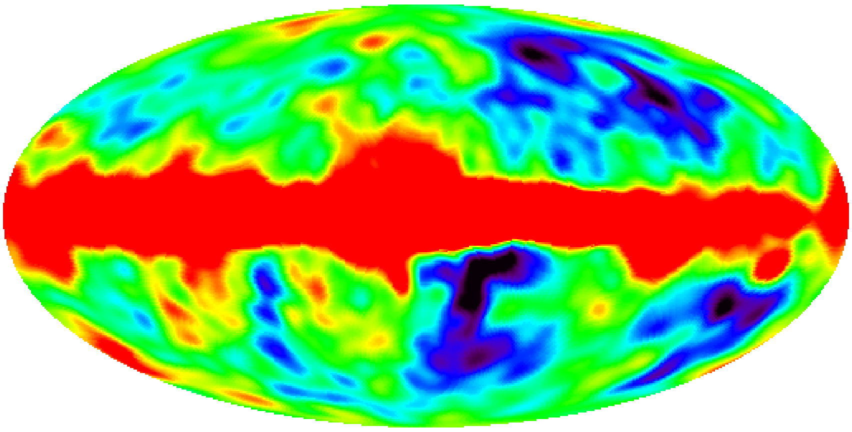
The CMB is highly isotropy, uniform to better than 1 part in 100,000. Any deviations from uniformity are measuring the fluctuations that grew by gravitational instability into galaxies and clusters of galaxies.

Images of the CMB are a full sky image, meaning that it looks like a map of the Earth unfolded from a globe. In this case, the globe is the celestial sphere and we are looking at a flat map of the sphere.

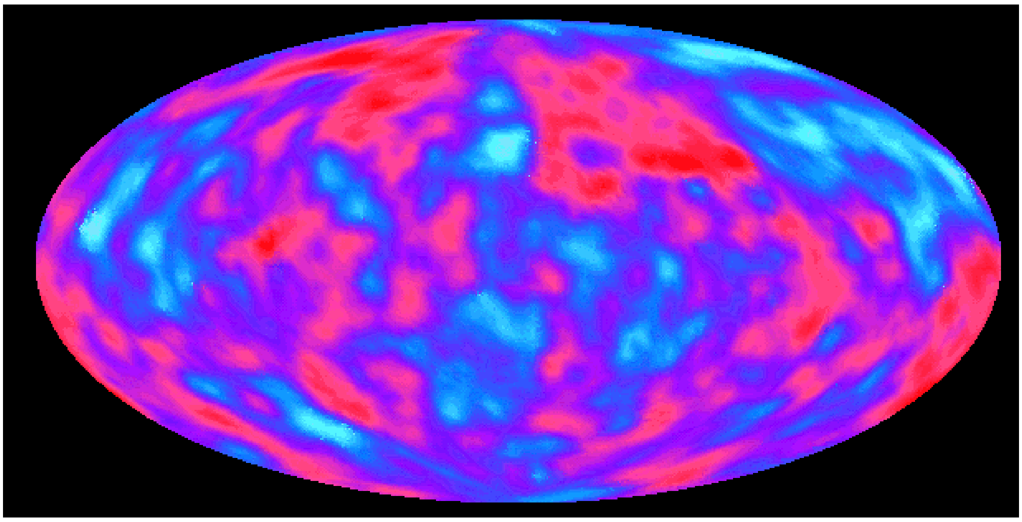
Maps of the CMB have to go through three stages of analysis to reveal the fluctuations associated with the early Universe. The raw image of the sky looks like the following, where red is hotter and blue is cooler:



The above image has a typical dipole appearance because our Galaxy is moving in a particular direction. The result is one side of the sky will appear redshifted and the other side of the sky will appear blueshifted. In this case, redshifting means the photons are longer in wavelength = cooler (so backwards from their name, they look blue in the above diagram). Removing the Galaxy's motion produces the following map:



This map is dominated by the far-infrared emission from gas in our own Galaxy. This gas is predominately in the plane of our Galaxy's disk, thus the dark red strip around the equator. The gas emission can be removed, with some assumptions about the distribution of matter in our Galaxy, to reveal the following map:



This CMB image is a picture of the last scattering epoch, i.e. it is an image of the moment when matter and photons decoupled, literally an image of the recombination wall. This is the last barrier to our observations about the early Universe, where the early epochs behind this barrier are not visible to us.

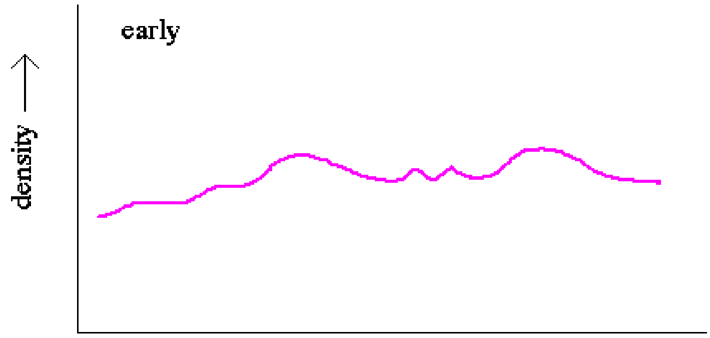
The clumpness of the CMB image is due to fluctuations in temperature of the CMB photons. Changes in temperature are due to changes in density of the gas at the moment of recombination (higher densities equal higher temperatures). Since these photons are coming to us from the last scattering epoch, they represent fluctuations in density at that time.

The origin of these fluctuations are primordial quantum fluctuations from the very earliest moments of are echo'ed in the CMB at recombination. Currently, we believe that these quantum fluctuations grew to greater than galaxy-size during the inflation epoch, and are the source of structure in the Universe.

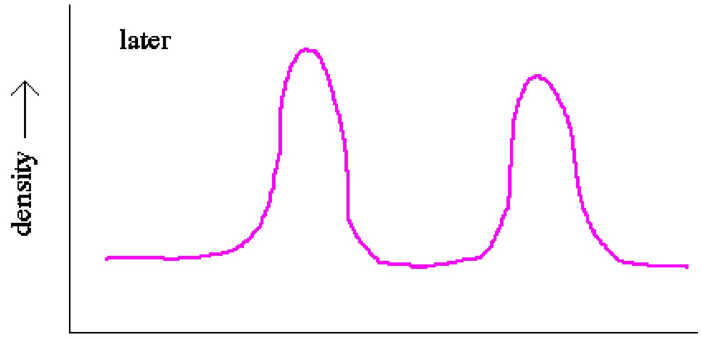
Fluctuations and the Origin of Galaxies :

The density fluctuations at recombination, as measured in the CMB, are too large and too low in amplitude to form galaxy sized clumps. Instead, they are the seeds for galaxy cluster-sized clouds that will then later break up into galaxies. However, in order to form cluster-sized lumps, they must grow in amplitude (and therefore mass) by gravitational instability, where the self-gravity of the fluctuation overcomes the gas pressure.

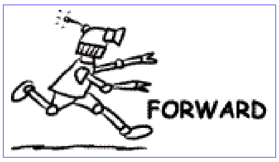
large scale fluctuations become gravitationally unstable and grow in amplitude




small scale fluctuations damp out with time




The CMB fluctuations are a link between Big Bang and the large scale structure of galaxies in the Universe, their distribution in terms of clusters of galaxies and filaments of galaxies that we observe around the Milky Way today.

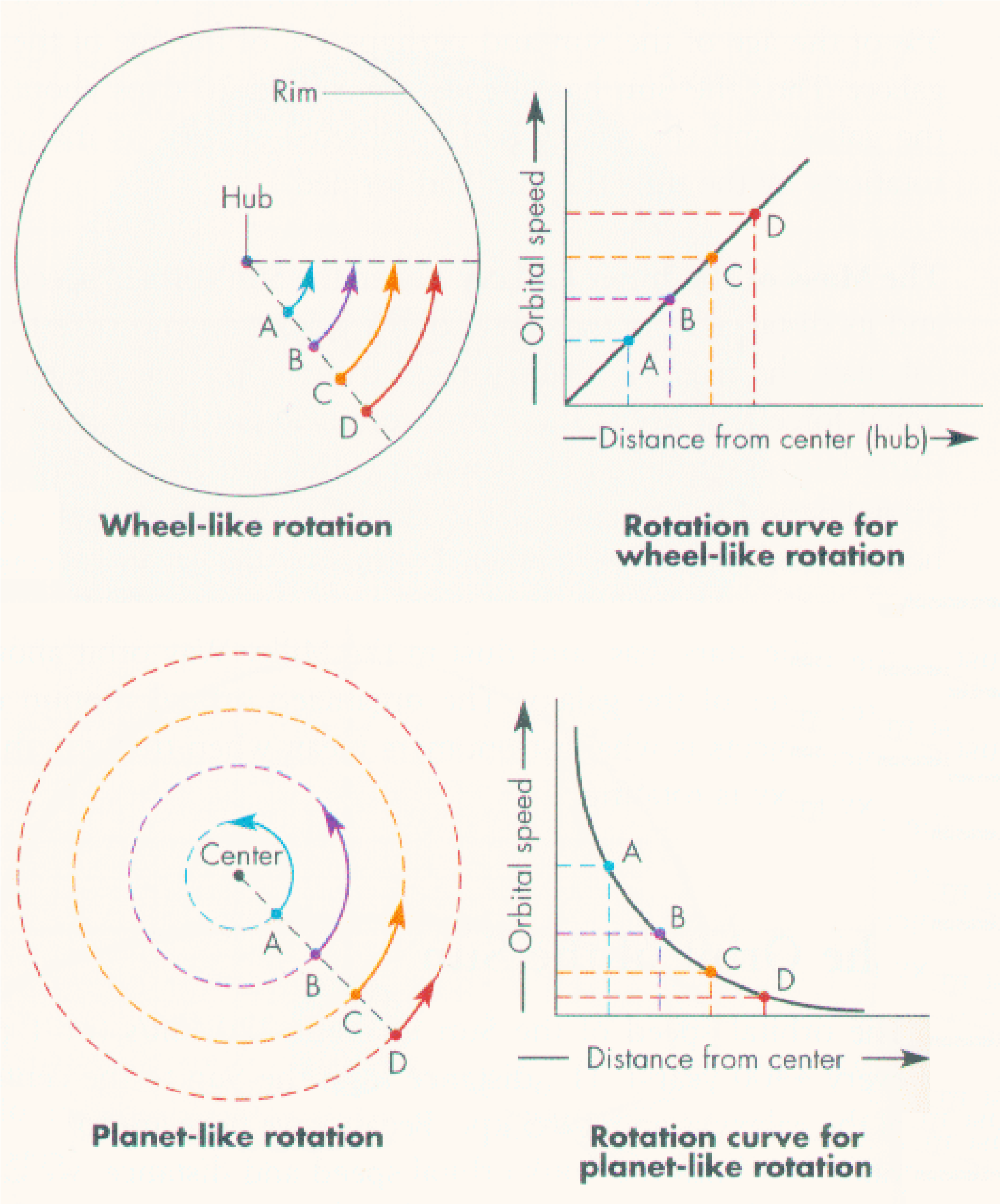





Rotation Curve of Galaxy:

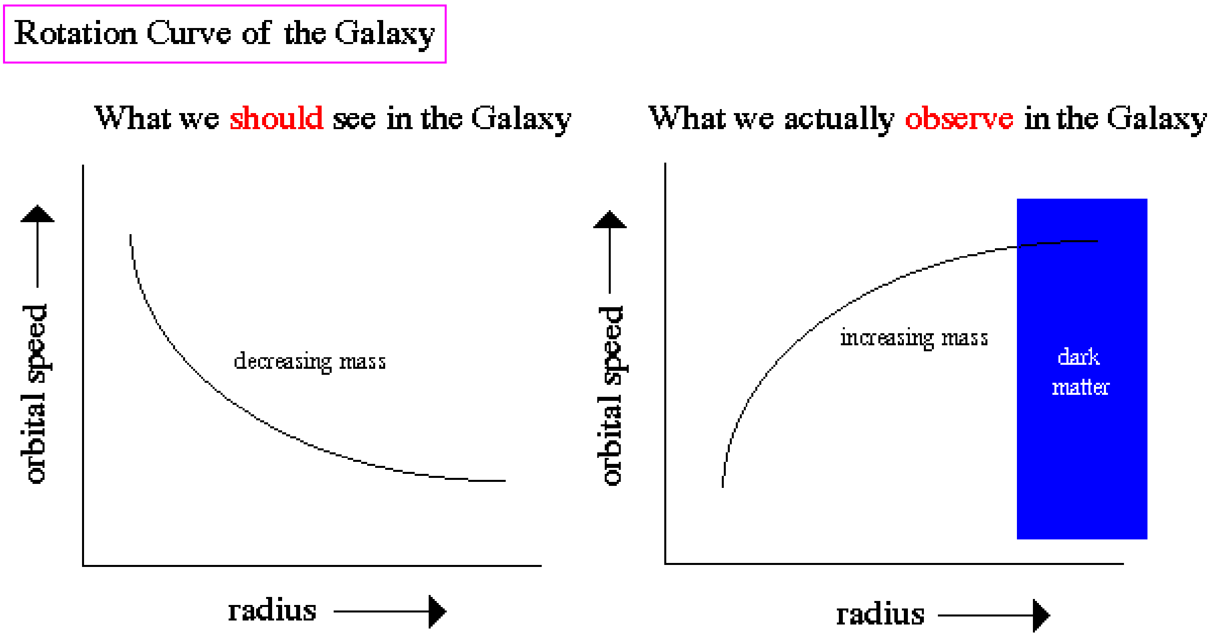
Dynamical studies of the Universe began in the late 1950's. This meant that instead of just looking and classifying galaxies, astronomers began to study their internal motions (rotation for disk galaxies) and their interactions with each other, as in clusters. The question was soon developed of whether we were observing the mass or the light in the Universe. Most of what we see in galaxies is starlight. So clearly, the brighter the galaxy, the more stars, therefore the more massive the galaxy. By the early 1960's, there were indications that this was not always true, called the missing mass problem.

The first indications that there is a significant fraction of missing matter in the Universe was from studies of the rotation of our own Galaxy, the Milky Way. The orbital period of the Sun around the Galaxy gives us a mean mass for the amount of material inside the Sun's orbit. But, a detailed plot of the orbital speed of the Galaxy as a function of radius reveals the distribution of mass within the Galaxy. The simplest type of rotation is wheel rotation shown below.




Rotation following Kepler's 3rd law is shown above as planet-like or differential rotation. Notice that the orbital speeds falls off as you go to greater radii within the Galaxy. This is called a Keplerian rotation curve.

To determine the rotation curve of the Galaxy, stars are not used due to interstellar extinction. Instead, 21-cm maps of neutral hydrogen are used. When this is done, one finds that the rotation curve of the Galaxy stays flat out to large distances, instead of falling off as in the figure above. This means that the mass of the Galaxy increases with increasing distance from the center.

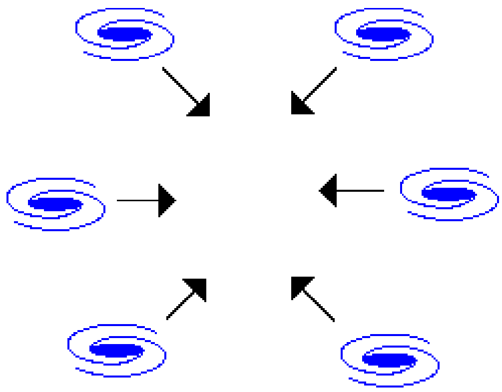



The surprising thing is there is very little visible matter beyond the Sun's orbital distance from the center of the Galaxy. So, the rotation curve of the Galaxy indicates a great deal of mass, but there is no light out there. In other words, the halo of our Galaxy is filled with a mysterious dark matter of unknown composition and type.

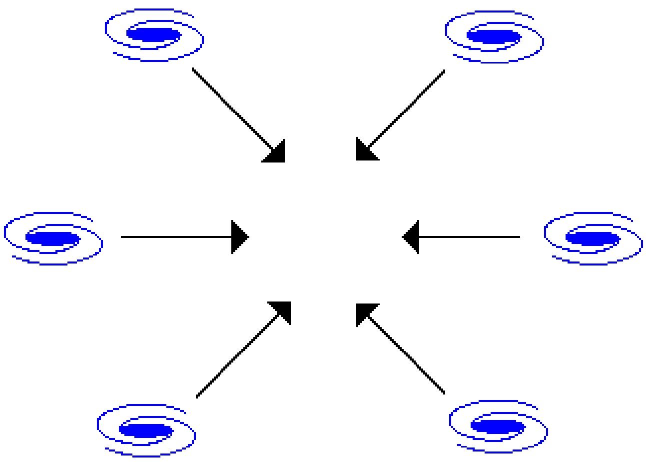
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Cluster Masses:

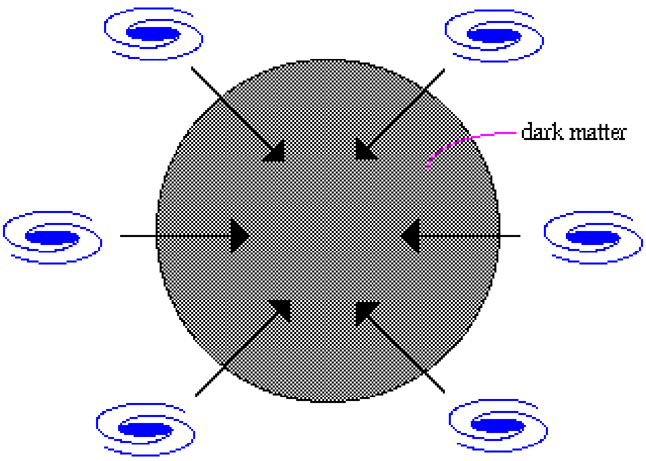
Most galaxies occupy groups or clusters with membership ranging from 10 to hundreds of galaxies. Each cluster is held together by the gravity from each galaxy. The more mass, the higher the velocities of the members, and this fact can be used to test for the presence of unseen matter.



The members of a cluster of galaxies move because of their mutual gravitational attraction.

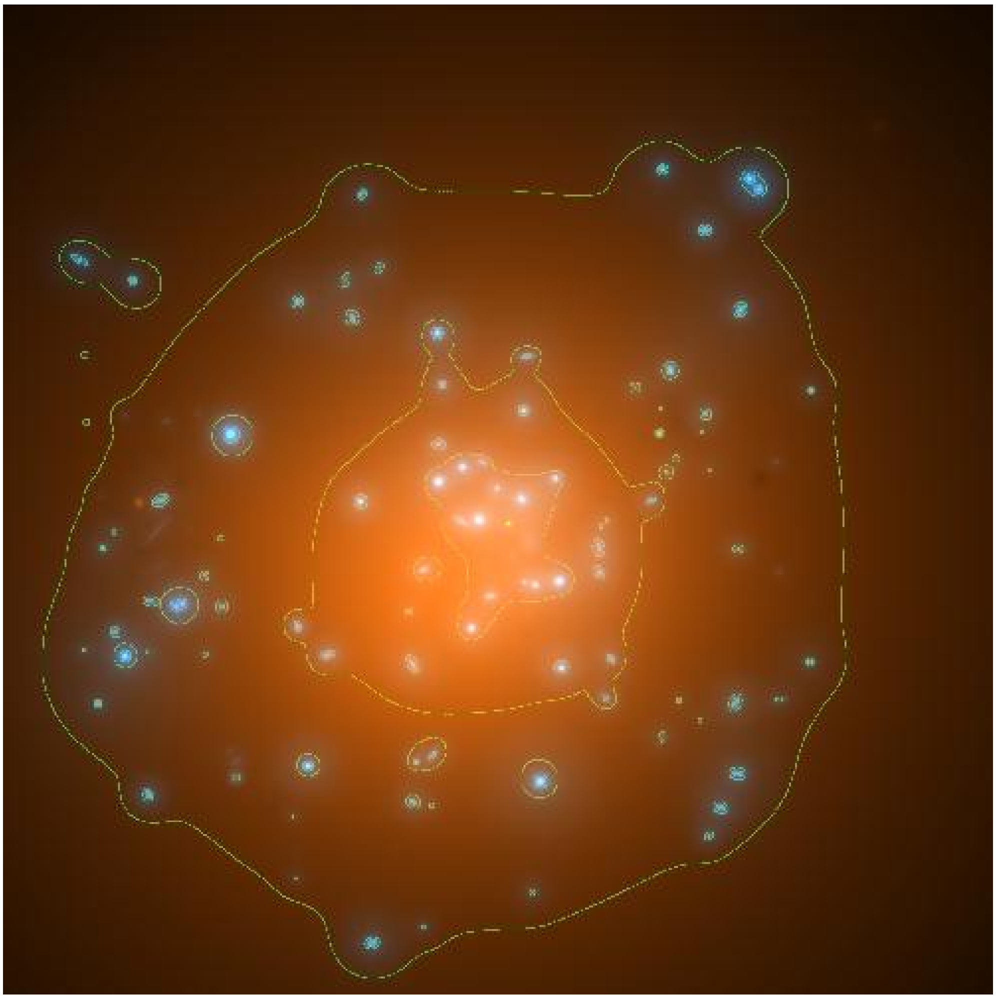


In most clusters, the velocity of the cluster galaxies is much higher than can be accounted for from the individual galaxy masses.




The result is there must be an unseen core of dark matter attracting the galaxies with more gravity and, therefore, more velocity.

When these measurements were performed, it was found that up to 95% of the mass in clusters is not seen, i.e. dark. Since the physics of the motions of galaxies is so basic (pure Newtonian physics), there is no escaping the conclusion that a majority of the matter in the Universe has not been identified, and that the matter around us that we call `normal' is special. The question that remains is whether dark matter is baryonic (normal) or a new substance, non-baryonic.

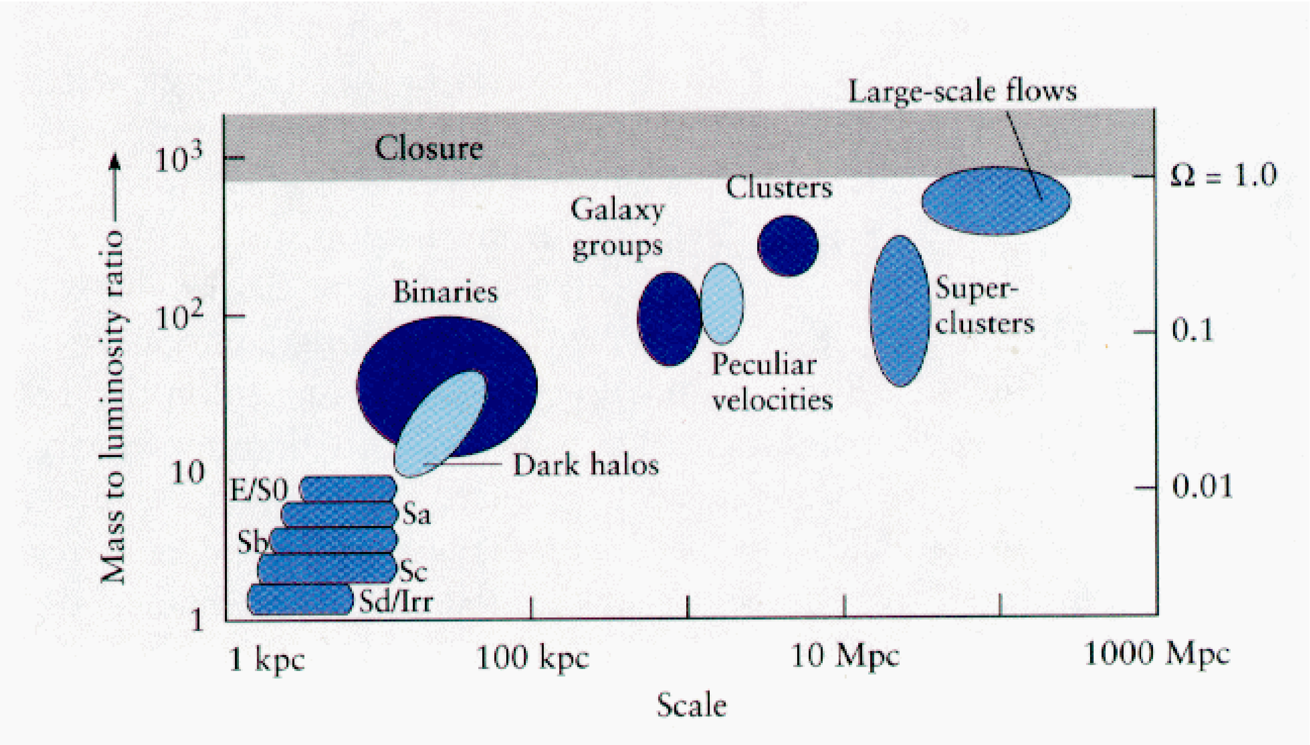


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<u>Mass-to-Luminosity Ratios</u>:

Exactly how much of the Universe is in the form of dark matter is a mystery and difficult to determine, obviously because its not visible. It has to be inferred by its gravitational effects on the luminous matter in the Universe (stars and gas) and is usually expressed as the mass-to-luminosity ratio (M/L). A high M/L indicates lots of dark matter, a low M/L indicates that most of the matter is in the form of baryonic matter, stars and stellar reminants plus gas.

A important point to the study of dark matter is how it is distributed. If it is distributed like the luminous matter in the Universe, that most of it is in galaxies. However, studies of M/L for a range of scales shows that dark matter becomes more dominate on larger scales.




Most importantly, on very large scales of 100 Mpc's (Mpc = megaparsec, one million parsecs and kpc = 1000 parsecs) the amount of dark matter inferred is near the value needed to close the Universe. Thus, it is for two reasons that the dark matter problem is important, one to determine what is the nature of dark matter, is it a new form of undiscovered matter? The second is the determine if the amount of dark matter is sufficient to close the Universe.

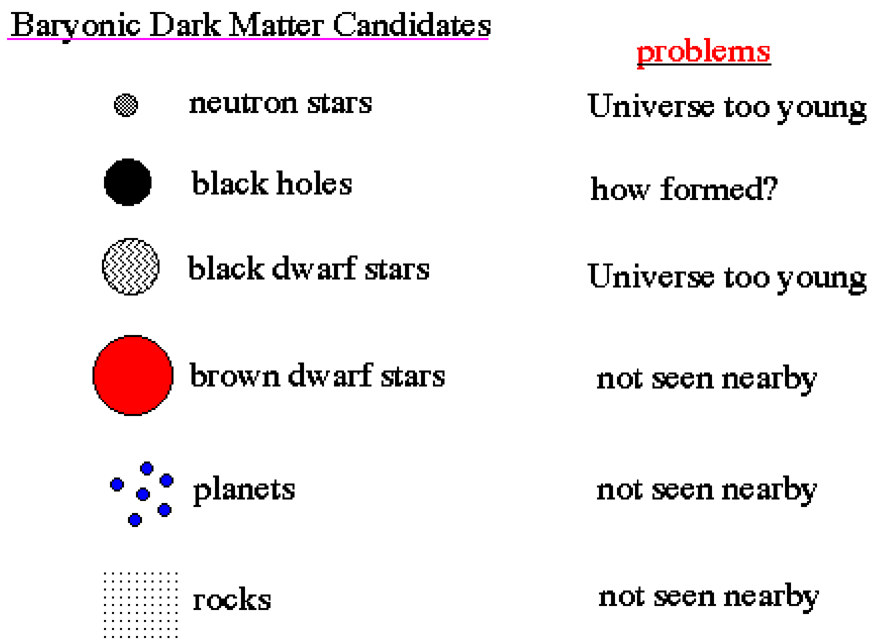
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Baryonic Dark Matter:

We know of the presence of dark matter from dynamical studies. But we also know from the abundance of light elements that there is also a problem in our understanding of the fraction of the mass of the Universe that is in normal matter or baryons. The fraction of light elements (hydrogen, helium, lithium, boron) indicates that the density of the Universe in baryons is only 2 to 4% what we measure as the observed density.

It is not too surprising to find that at least some of the matter in the Universe is dark since it requires energy to observe an object, and most of space is cold and low in energy. Can dark matter be some form of normal matter that is cold and does not radiate any energy? For example, dead stars?

Once a normal star has used up its hydrogen fuel, it usually ends its life as a white dwarf star, slowly cooling to become a black dwarf. However, the timescale to cool to a black dwarf is thousands of times longer than the age of the Universe. High mass stars will explode and their cores will form neutron stars or black holes. However, this is rare and we would need 90% of all stars to go supernova to explain all of the dark matter.



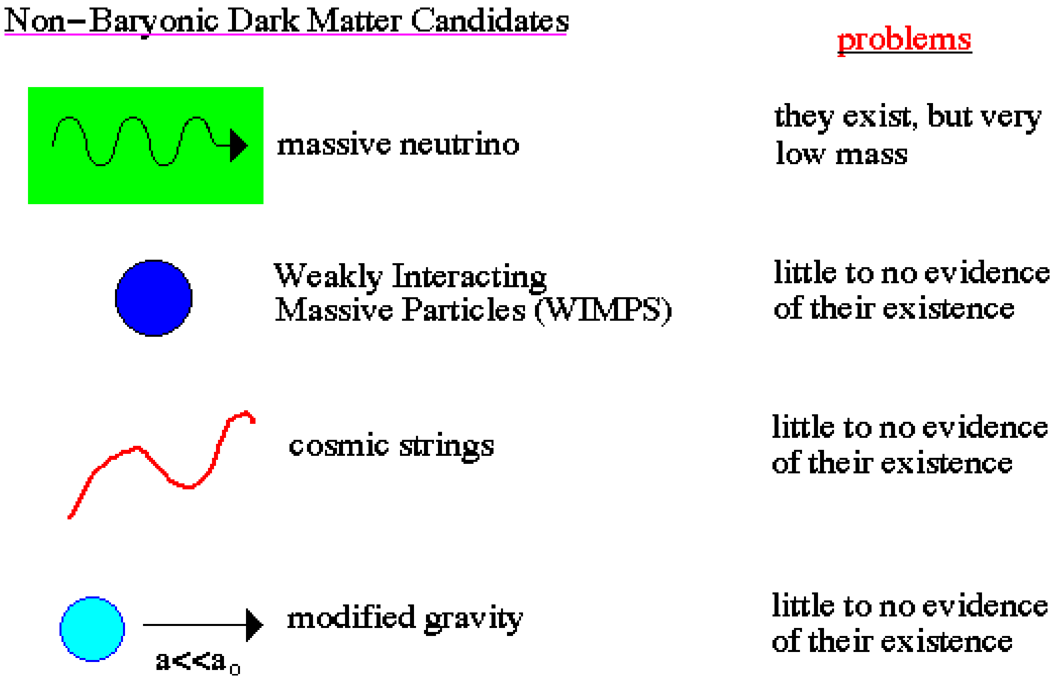

Another avenue of thought is to consider low mass objects. Stars that are very low in mass fail to produce their own light by thermonuclear fusion. Thus, many, many brown dwarf stars could make up the dark matter population. Or, even smaller, numerous Jupiter-sized planets, or even plain rocks, would be completely dark outside the illumination of a star. The problem here is that to make-up the mass of all the dark matter requires huge numbers of brown dwarfs, and even more Jupiter's or rocks. We do not find many of these objects nearby, so to presume they exist in the dark matter halos is unsupported.

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Non-Baryonic Dark Matter:

An alternative idea is to consider forms of dark matter not composed of quarks or leptons, rather made from some exotic material. If the neutrino has mass, then it would make a good dark matter candidate since it interacts weakly with matter and, therefore, is very hard to detect. However, neutrinos formed in the early Universe would also have mass, and that mass would have a predictable effect on the cluster of galaxies, which is not seen.

Another suggestion is that some new particle exists similar to the neutrino, but more massive and, therefore, more rare. This Weakly Interacting Massive Particle (WIMP) would escape detection in our modern particle accelerators, but no other evidence of its existence has been found.



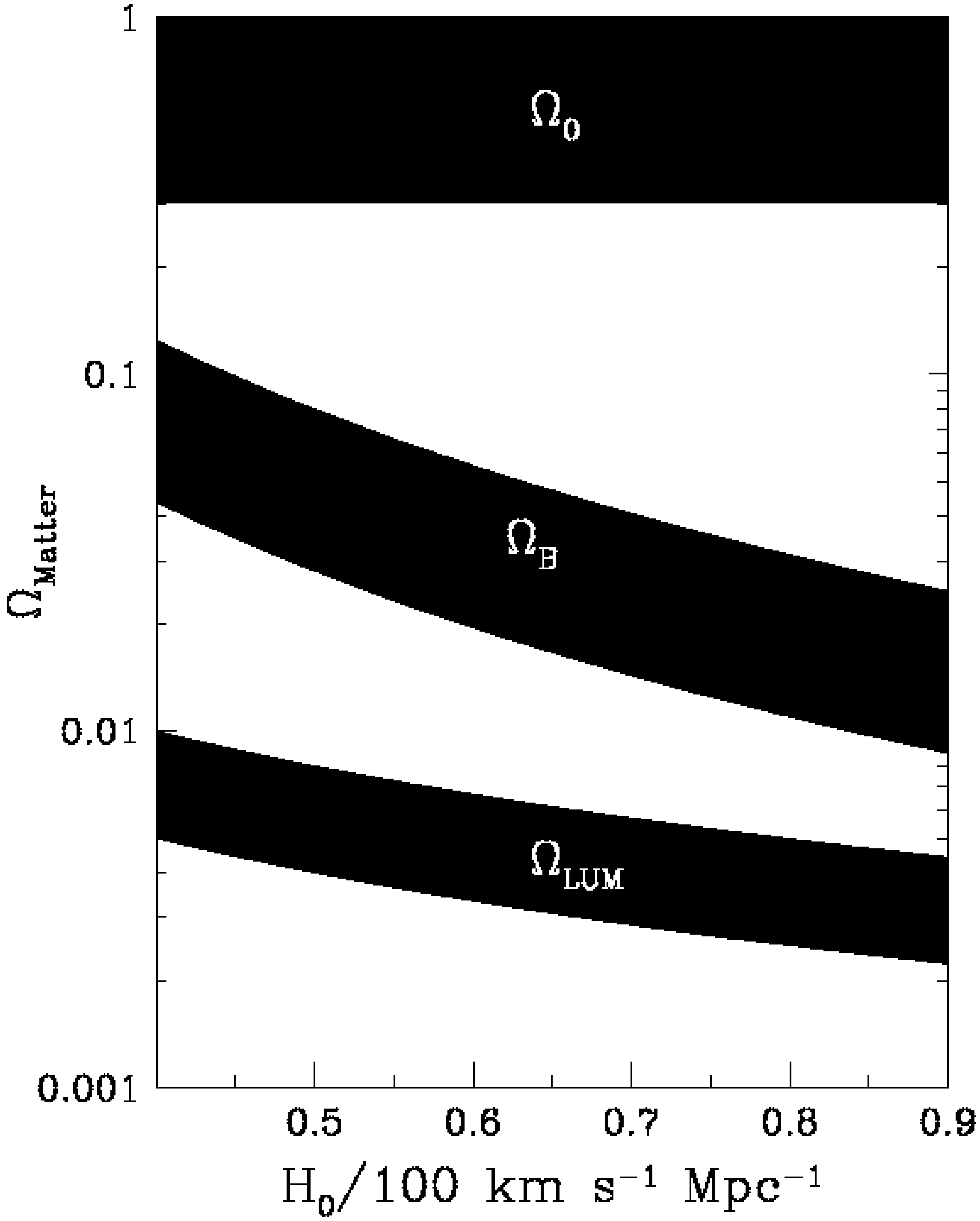

The more bizarre proposed solutions to the dark matter problem require the use of little understood relics or defects from the early Universe. One school of thought believes that topological defects may have appears during the phase transition at the end of the GUT era. These defects would have had a string-like form and, thus, are called cosmic strings. Cosmic strings would contain the trapped remnants of the earlier dense phase of the Universe. Being high density, they would also be high in mass but are only detectable by their gravitational radiation.

Lastly, the dark matter problem may be an illusion. Rather than missing matter, gravity may operate differently on scales the size of galaxies. This would cause us to overestimate the amount of mass, when it is the weaker gravity to blame. This is no evidence of modified gravity in our laboratory experiments to date.

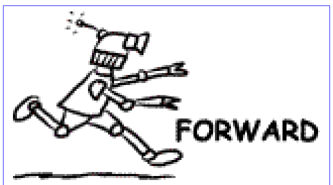
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Current View of Dark Matter:

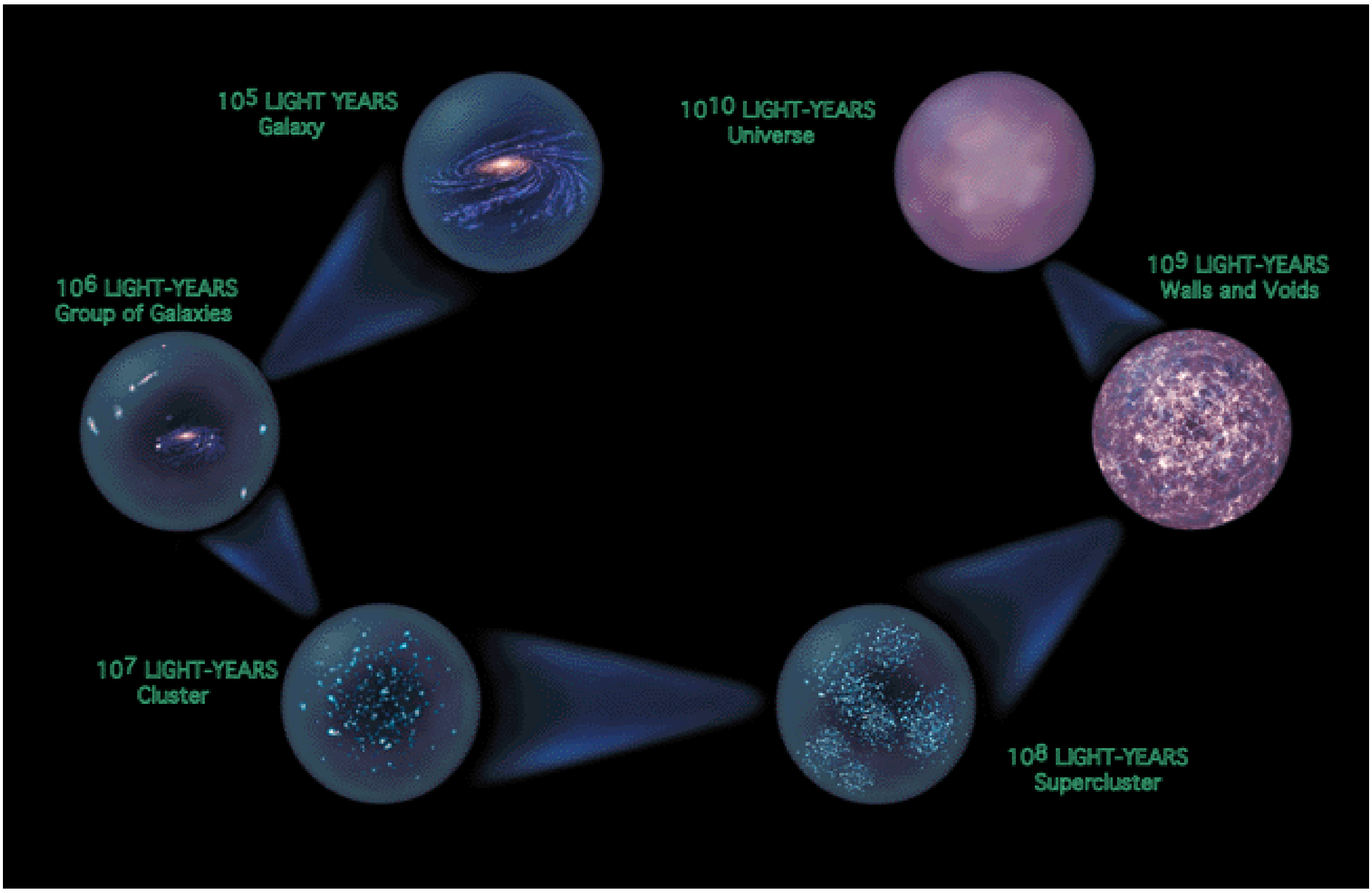
The current observations and estimates of dark matter is that 1/2 of dark matter is probably in the form of massive neutrinos, even though that mass is uncertain. The other 1/2 is in the form of stellar remnants and low mass, brown dwarfs. However, the combination of both these mixtures only makes 10 to 20% the amount mass necessary to close the Universe. Thus, the Universe appears to be open.




Summary of knowledge of $\Omega$. The lowest band is luminous matter, in the form of bright stars and related material; the middle band is the big-bang nucleosynthesis determination of the density of baryons; the upper region is the estimate of $\Omega_{Matter}$ based upon the peculiar velocities of galaxies. The gaps between the bands illustrate the two dark matter problems: most of the ordinary matter is dark and most of the matter is nonbaryonic.





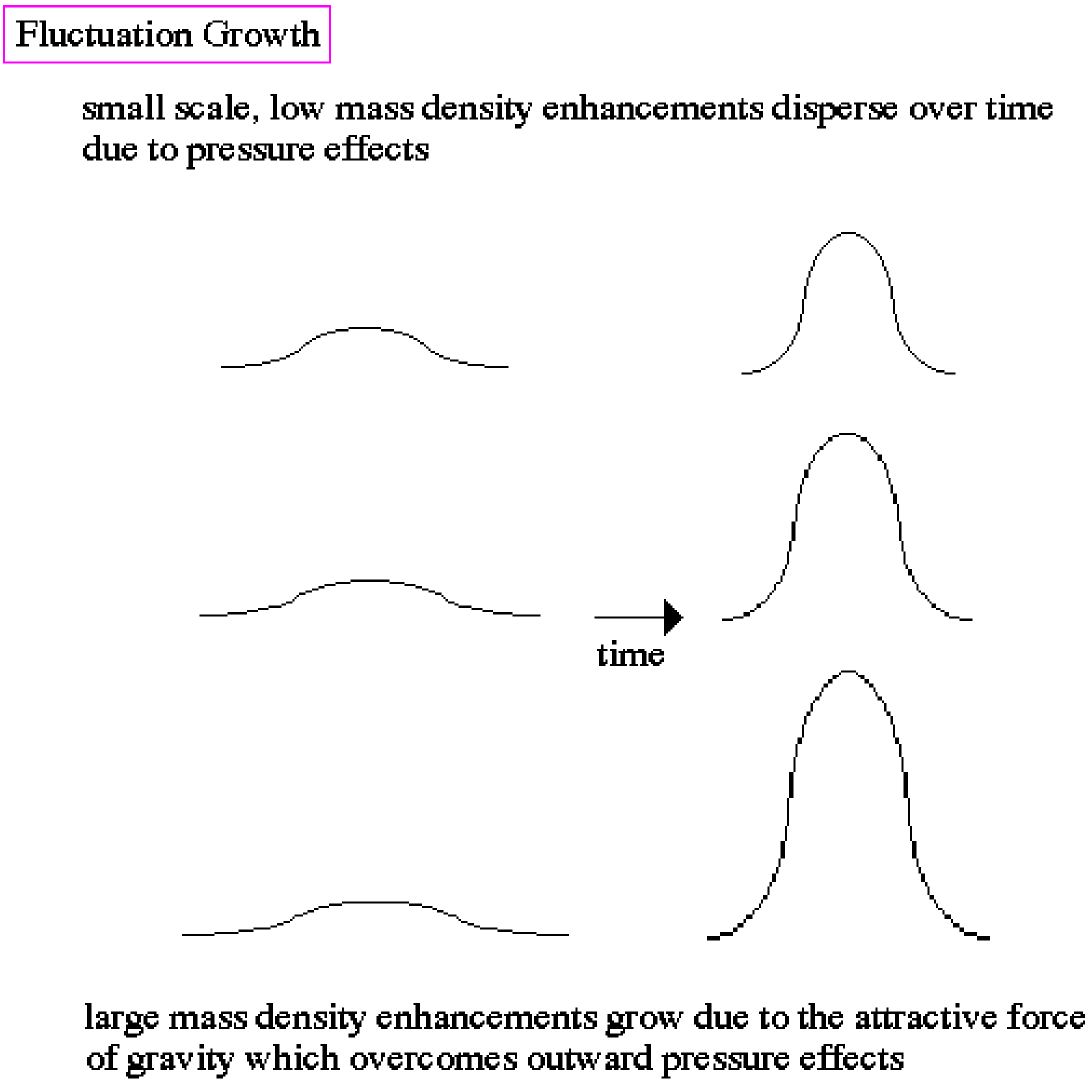




Origin of Structure :

As we move forward in time from the beginning of the Universe we pass through the inflation era, baryongenesis, nucleosynthesis and radiation decoupling. The culmination is the formation of the structure of matter, the distribution of galaxies in the Universe.

During radiation era growth of structure is suppressed by the tight interaction of photons and matter. Matter was not free to response to its own gravitational force, so density enhancements from the earliest times could not grow.

Density enhancements at the time of recombination (having their origin in quantum fluctuations that expanded to galaxy-sized objects during the inflation era) have two routes to go. They can grow or disperse.



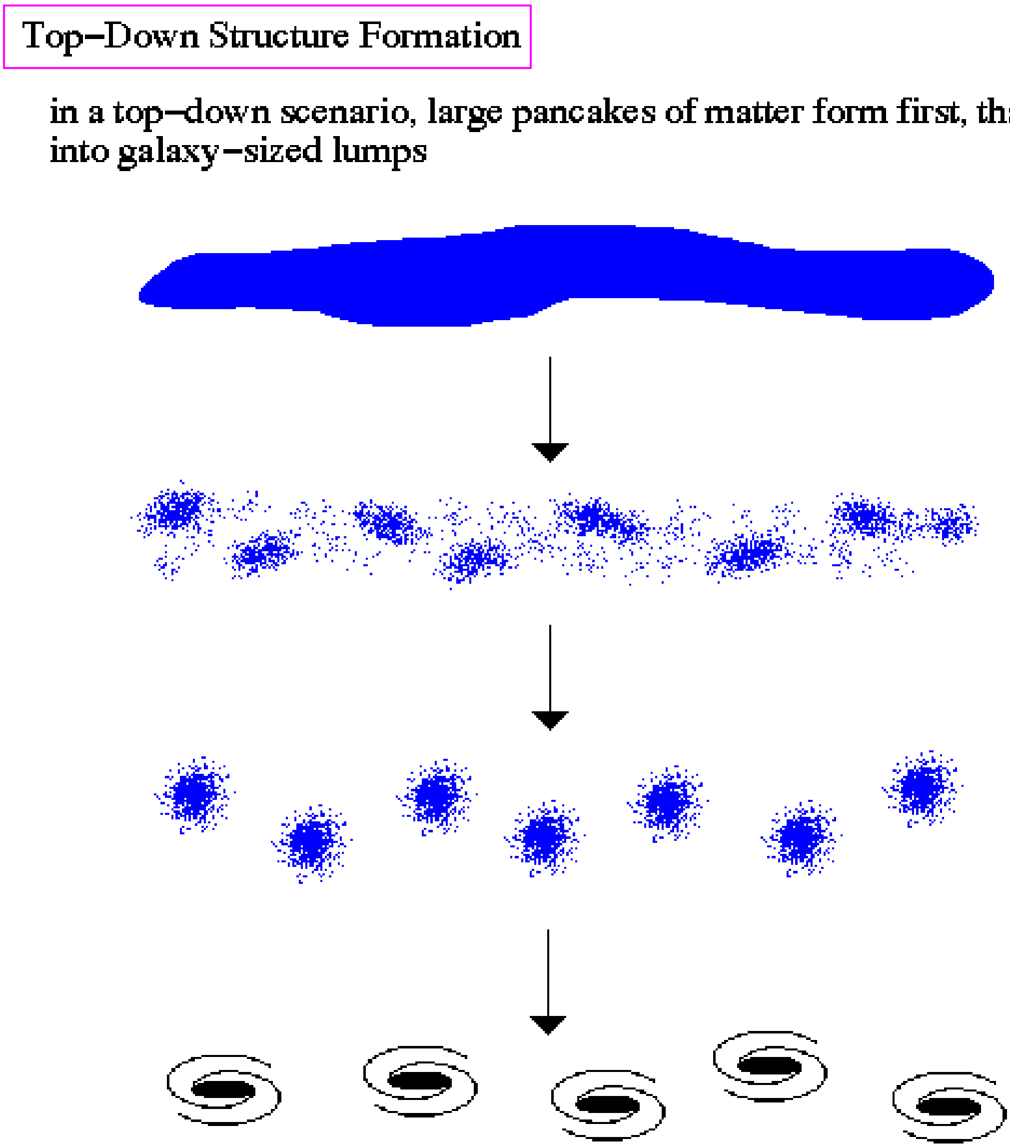

The `pressure effects' that density enhancements experience are due to the expanding Universe. The space itself between particles is expanding. So each particle is moving away from each other. Only if there is enough matter for the force of gravity to overcome the expansion do density enhancements collapse and grow.

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Top-Down Scenario:

Structure could have formed in one of two sequences: either large structures the size of galaxy clusters formed first, than latter fragmented into galaxies, or dwarf galaxies formed first, than merged to produce larger galaxies and galaxy clusters.

The former sequence is called the top-down scenario, and is based on the principle that radiation smoothed out the matter density fluctuations to produce large pancakes. These pancakes accrete matter after recombination and grow until they collapse and fragment into galaxies.

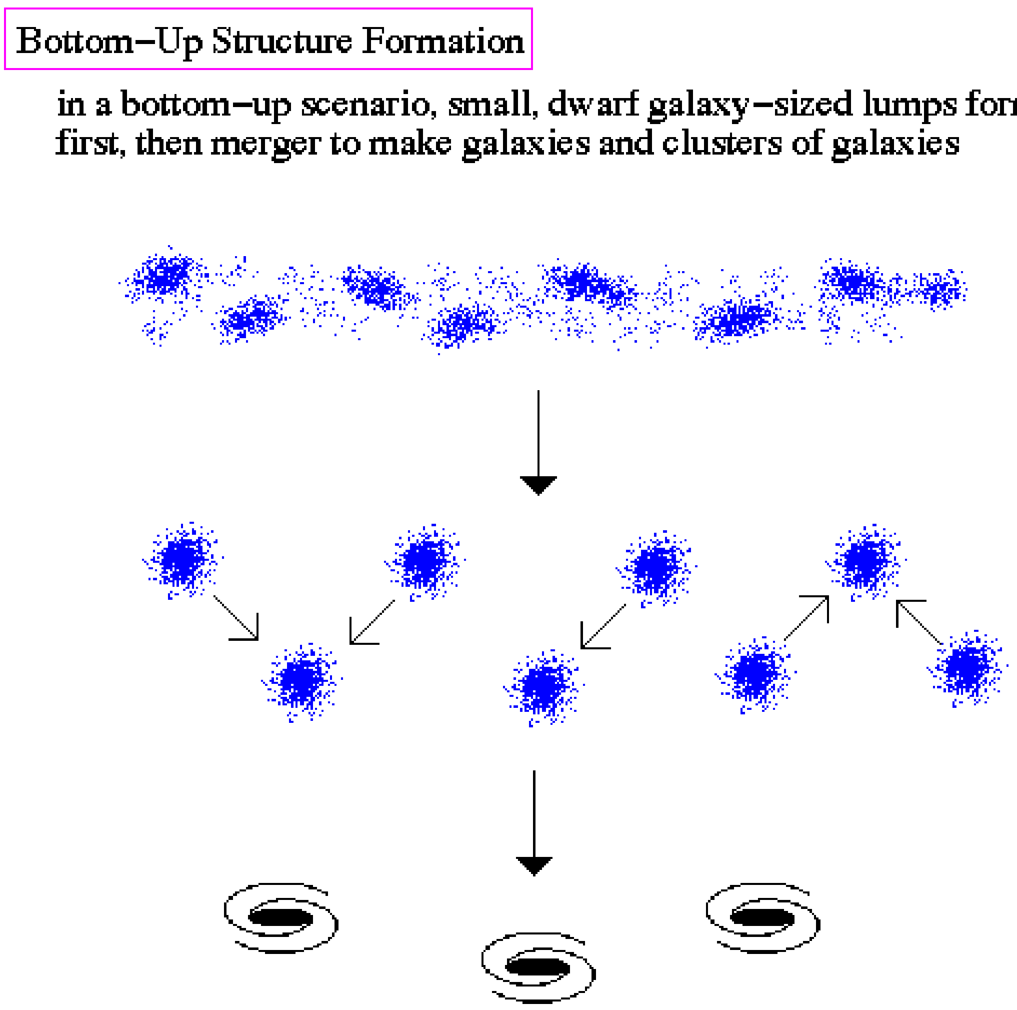



This scenario has the advantage of predicting that there should be large sheets of galaxies with low density voids between the sheets. Clusters of galaxies form where the sheets intersect.

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Bottom-Up Scenario:

The competing scenario is one where galaxies form first and merge into clusters, called the bottom-up scenario. In this scenario, the density enhancements at the time of recombination were close to the size of small galaxies today. These enhancements collapsed from self-gravity into dwarf galaxies.




Once the small galaxies are formed, they attract each other by gravity and merge to form larger galaxies. The galaxies can then, by gravity, cluster together to form filaments and clusters. Thus, gravity is the mechanism to form larger and larger structures.

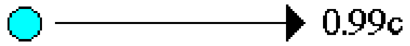
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Hot Dark Matter vs. Cold Dark Matter :

Each scenario of structure formation has its own predictions for the appearance of the Universe today. Both require a particular form for dark matter, a particular type of particle that makes up the 90% of the Universe not visible to our instruments. These two forms of dark matter are called Hot and Cold.

## Hot Dark Matter (HDM)

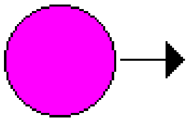
top–down scenarios require that dark matter be composed of a weakly interacting, high velocity particle




a massive neutrino is a good candidate for an HDM particle

## Cold Dark Matter (CDM)

bottom–up scenarios require that dark matter be composed of a highly massive, slow moving particles



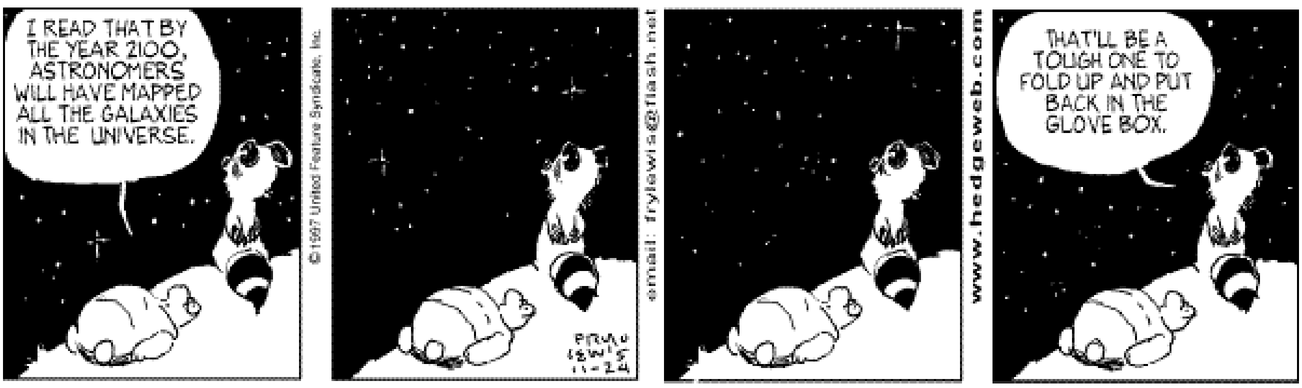
note that neither of these particles are baryons, the ordinary matter makes up stars or planets

HDM produces large, smooth features since it travels at high velocity. Massive neutrinos move at near the speed of light, yet interact very weakly with matter so can serve to smooth out large density enhancements.

CDM, on the other hand, is slow moving and, therefore, clumps into small regions. Large scale features are suppressed since the small clumps grow to form small galaxies.

There is strong evidence that galaxies formed before clusters, in the sense that the stars in galaxies are 10 to 14 billion years old, but many clusters of galaxies are still forming today. This would rule against the top-down scenario and support the bottom-up process.

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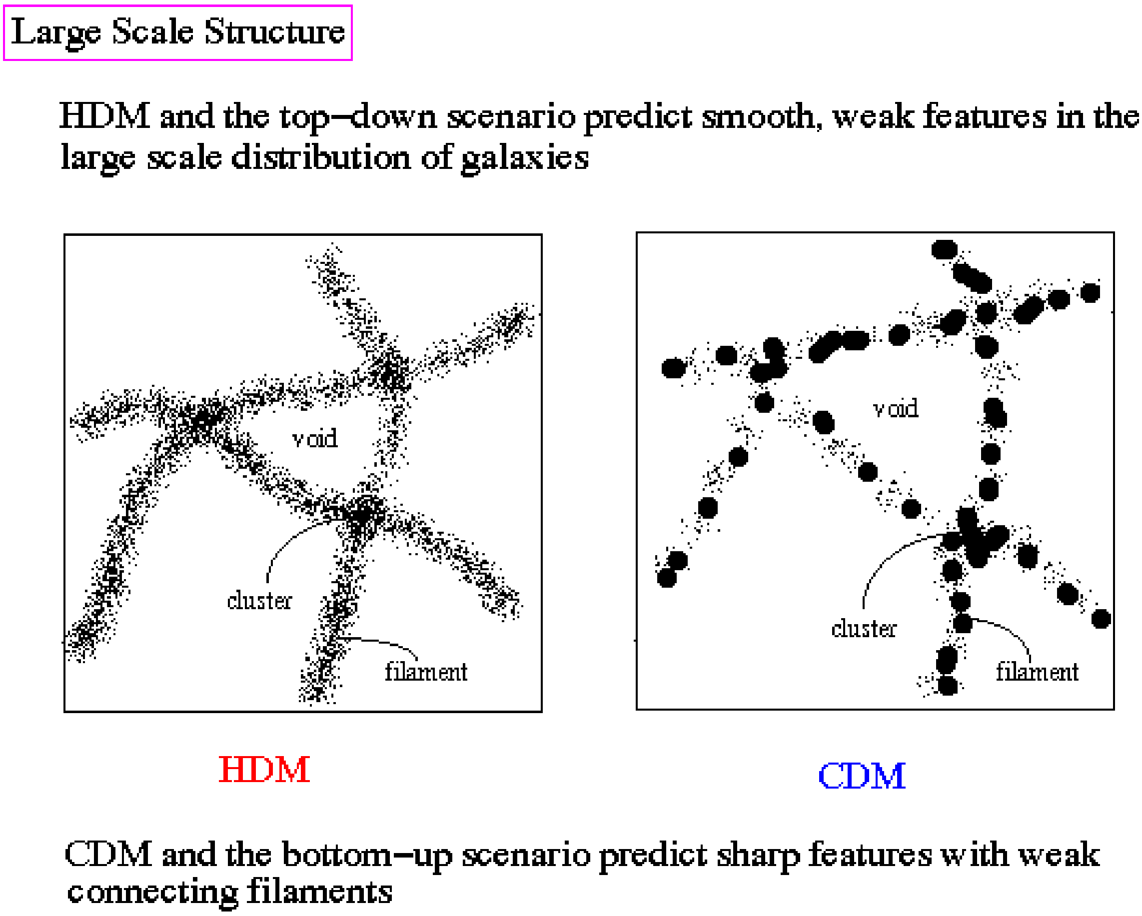



Large Scale Structure :

Galaxies in the Universe are not distributed evenly, i.e. like dots in a grid. Surveys of

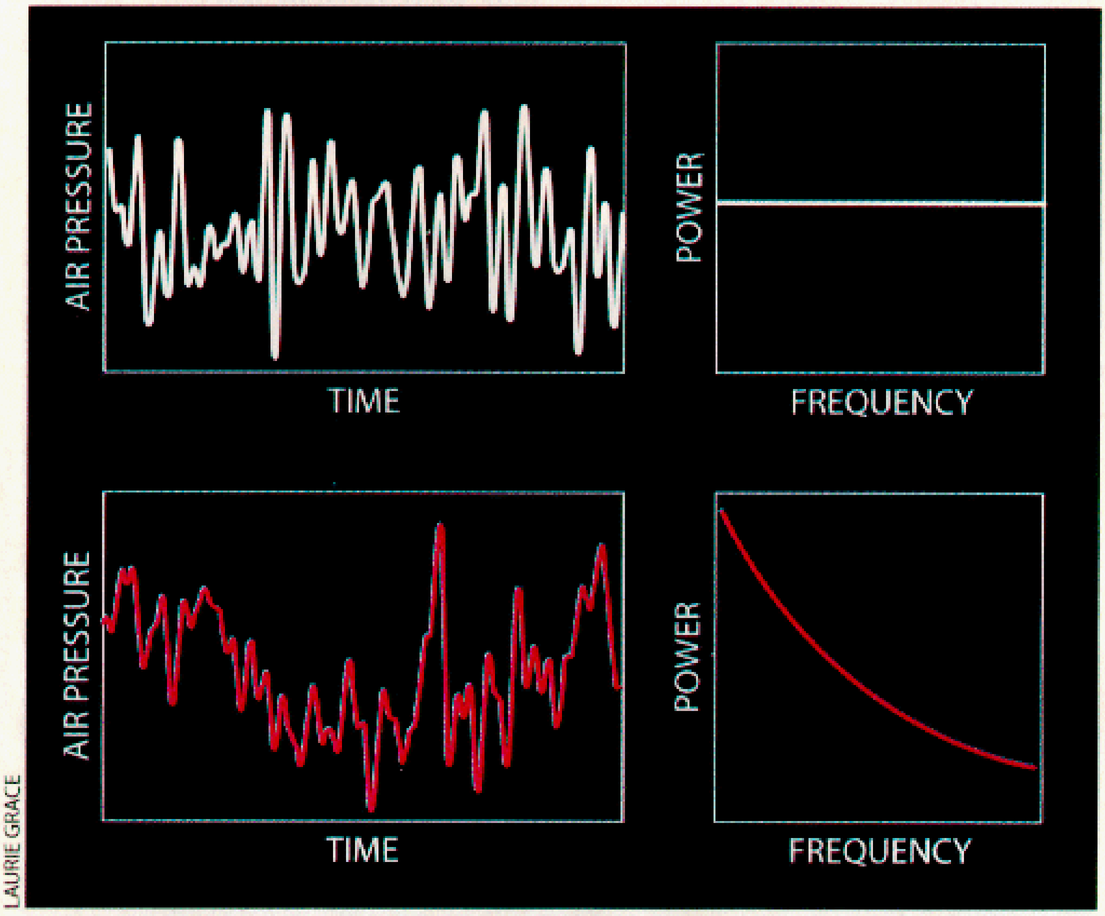
galaxy positions, e.g. maps of galaxies, have shown that galaxies have large scale structure in terms of clusters, filaments and voids.

The clusters, filaments and voids reflect the initial fluctuations at recombination, plus any further evolution as predicted by HDM or CDM models. CDM and HDM models have particular predictions that can be tested by maps or redshift surveys that cover 100's of millions of light-years.

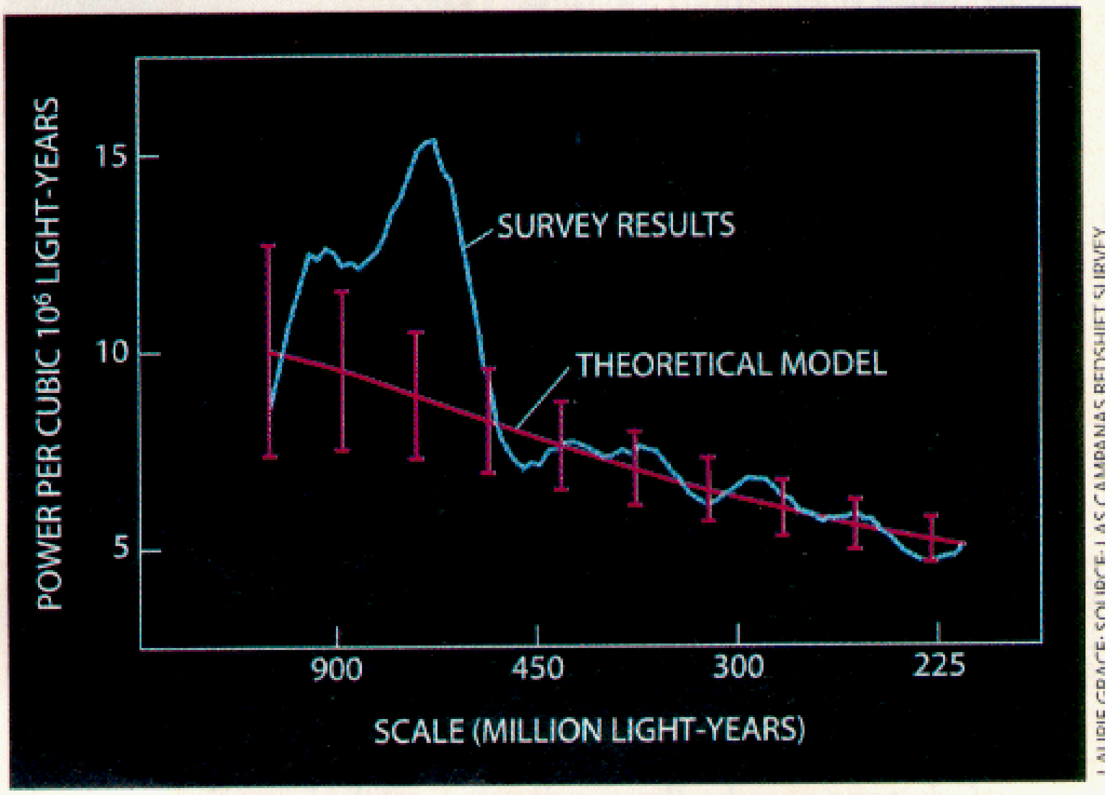



Interestingly enough, the real distribution of galaxies from redshift surveys is exactly in-between the HDM and CDM predictions, such that a hybrid model of both HDM and CDM is needed to explain what we see.

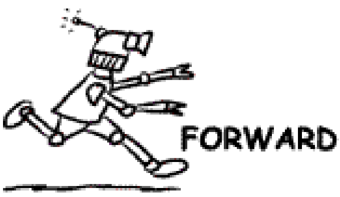
The mapping of large scale structure also has an impact on determining is the Universe is open or closed. Galaxies on the edges of the filaments will move in bulk motion towards concentrations of other galaxies and dark matter. These large scale flows can be used to determine the density of large regions of space, then extrapolated to determine the mean density of the Universe.




WHITE AND PINK NOISE surround us. White noise, the grating sound of static on a badly tuned radio or television, is completely random. The sound fluctuates from instant to instant without any pattern (*top*). Pink noise, the sound of a waterfall or waves crashing on the beach, is fractal (*bottom*). This distinction is reflected in the power spectra (*graphs at right*): white noise has equal power at all frequencies, but pink noise has more power in the bass than in the treble, in inverse proportion to the frequency.




POWER SPECTRUM of the cosmos, as measured by the Las Campanas survey (*blue line*), generally follows the prediction of the cold dark matter model (*pink*). But the power increases dramatically on scales of 600 million to 900 million light-years. This discrepancy means that the universe is much clumpier on those scales than current theories can explain.






## Galaxy Formation :

Galaxies are the basic unit of cosmology. They contain stars, gas, dust and alot of dark matter. They are the only `signposts' from here to the edge of the Universe and contain the fossil clues to this earlier time.

The physics of galaxy formation is complicated because it deals with the dynamics of stars (gravitational interaction), thermodynamics of gas and energy production of stars. For example, stars form from gas clouds, but new stars heat these clouds, which dissipates them and stops the formation of other stars.

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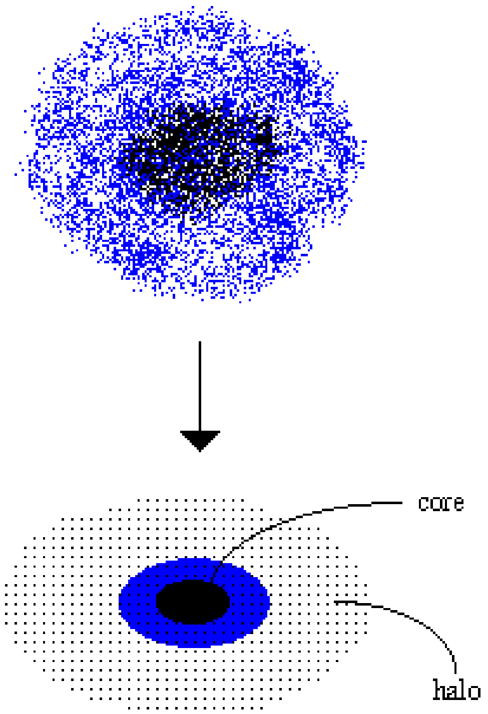
## Protogalaxies:

After recombination, density enhancements either grew or dispersed. According to our hybrid top-down/bottom-up scenario, an assortment of enhancements formed of various sizes. Small, dense ones collapsed first, large ones formed slower and fragmented as they collapsed.

The first lumps that broke free of the Universe's expansion were mostly dark matter and some neutral hydrogen with a dash of helium. Once this object begins to collapse under its own gravity, it is called a protogalaxy. The first protogalaxies appeared about 14 billion years ago.

Protogalaxy

a lump of dark matter and gas from the time of recombination collapses under its own gravity to form a protogalaxy




gravity separates out the protogalaxy into a core and halo. The baryons that make up the gas can interact to lose energy and fall to the core of the protogalaxy. The dark matter, which only weakly interacts, remains in the halo.

Note that dark matter and ordinary matter (in the form of hydrogen and helium gas at this time) separate at this time. Gas can dissipate its energy through collisions. The atoms in the gas collide and heat up, the heat is radiated in the infrared (light) and the result is the gas loses energy, moves slowly = collapses to the center. Dark matter does not interact this way and continues to orbit in the halo.

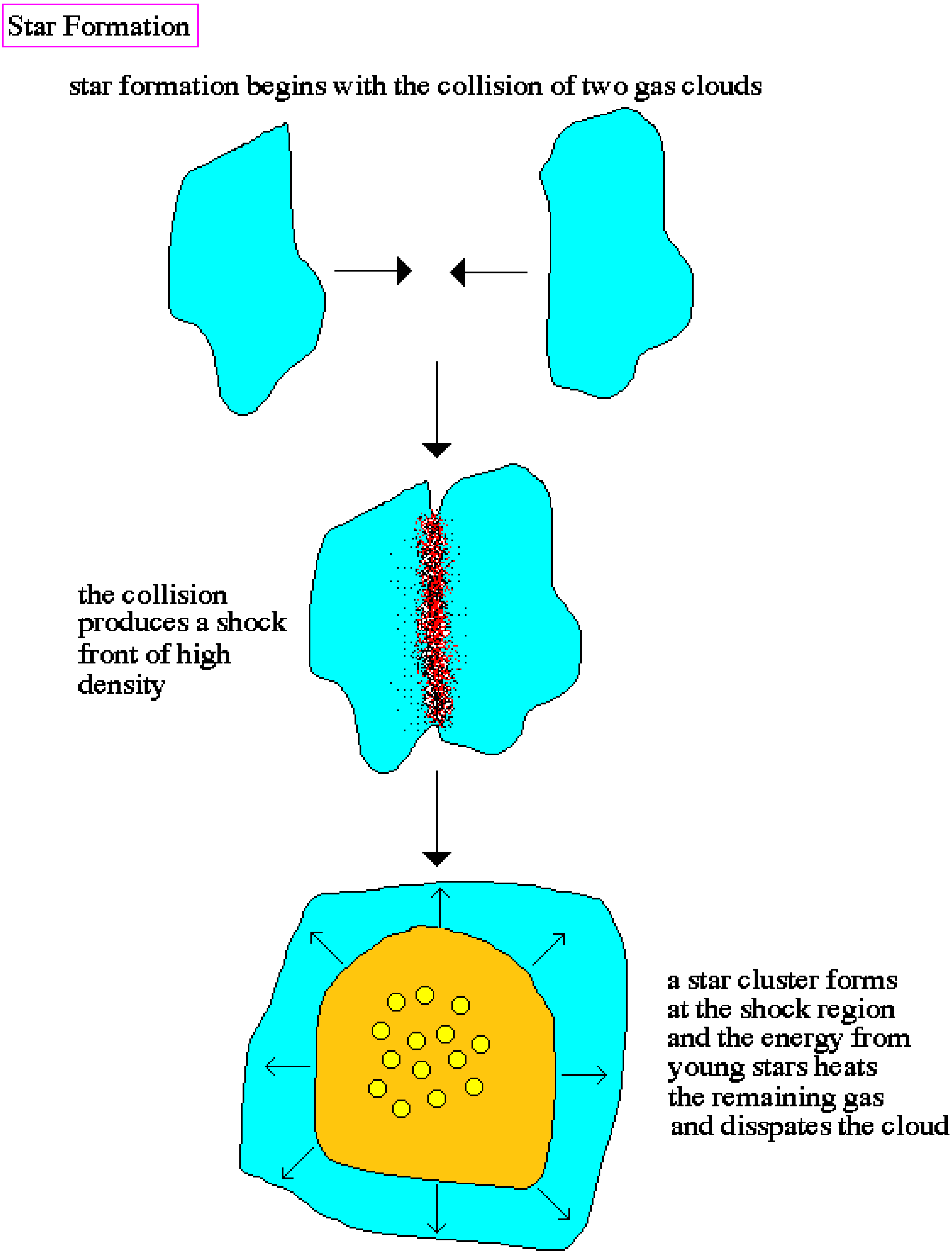
Even though there are no stars yet, protogalaxies should be detectable by their infrared emission (i.e. their heat). However, they are very faint and very far away (long time ago), so our technology has not been successful in discovering any at this time.

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Formation of the First Stars :

As the gas in the protogalaxy loses energy, its density goes up. Gas clouds form

and move around in the protogalaxy on orbits. When two clouds collide, the gas is compressed into a shock front.




The first stars in a galaxy form in this manner. With the production of its first

photons by thermonuclear fusion, the galaxy becomes a primeval galaxy.

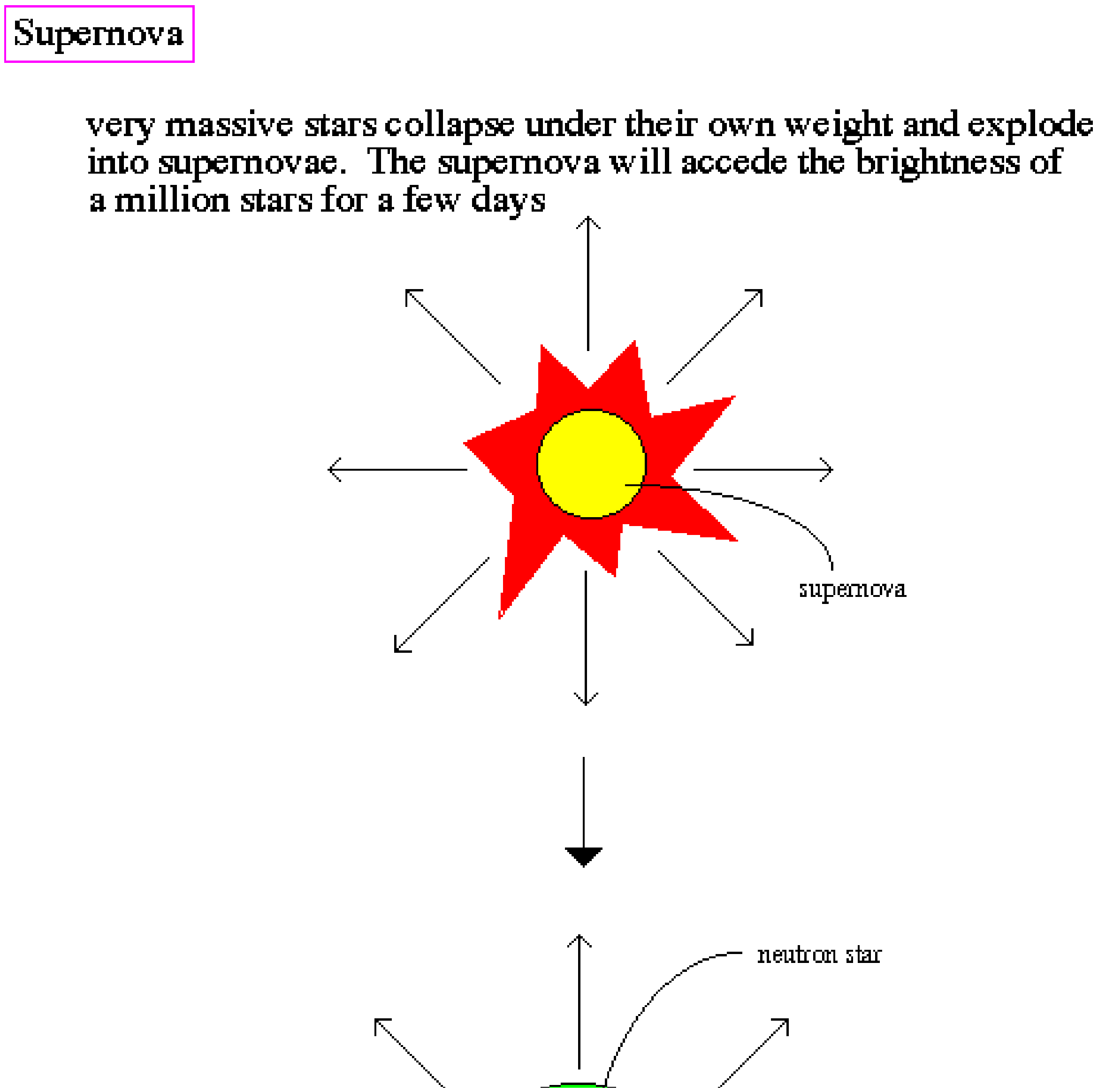
Star formation sites in primeval galaxies are similar to star forming regions in present-day galaxies. A grouping of young stars embedded in a cloud of heated gas. The gas will eventually be pushed away from the stars to leave a star cluster.

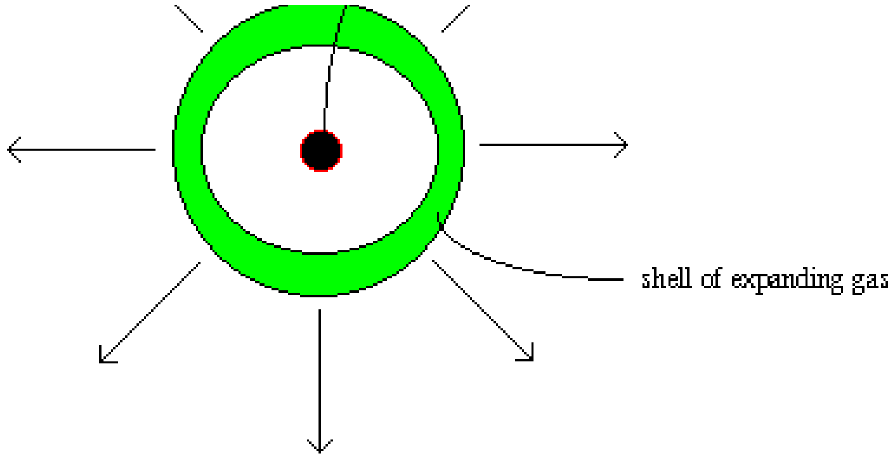
The first stars in our Galaxy are the globular star clusters orbiting outside the stellar disk which contains the spiral arms. Most galaxies with current star formation have an underlying distribution of old stars from the first epoch of star formation 14 billion years ago.

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Stellar Death :

The most massive stars end their lives as supernova, the explosive destruction of a star. Supernova's occur when a star uses up its interior fuel of hydrogen and collapses under its own weight. The infalling hydrogen from the star's outer envelope hits the core and ignites explosively.






a gas shell, enriched in heavy elements, is ejected into the galaxy

During the explosion, runaway fusion occurs and all the elements in the periodic table past lithium are produced. This is the only method of producing the heavy elements and is the origin to all the elements in your body.

This shell of enriched gas is ejected into the galaxy's gas supply. Thus, the older a galaxy, the more rich its gas is in heavy elements, a process called chemical evolution.

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Ellipticals vs. Spirals :

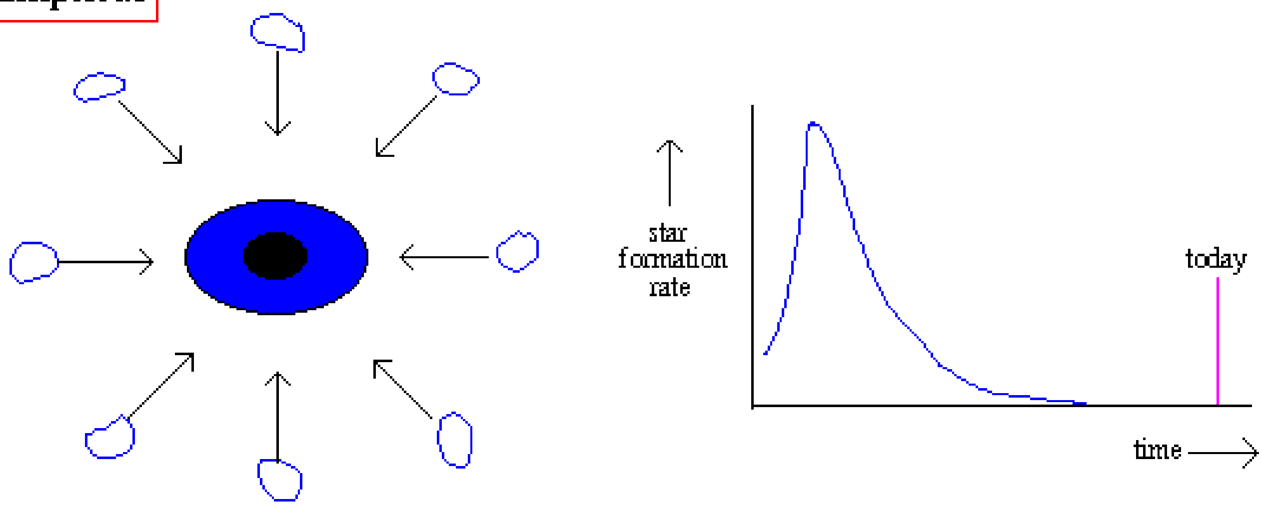
The two most distinct galaxy types are ellipticals and spirals. Ellipticals have no ongoing star formation today, spirals have alot. Assuming that ellipticals and spirals are made from the same density enhancements at the time of recombination, why did they evolve into very difference appearances and star formation rates?

The answer is how rapid their initial star formation was when they formed. If star formation proceeds slowly, the gas undergoes collisions and conservation of angular momentum forms a disk (a spiral). If star formation is rapid and all the gas is used up in an initial burst, the galaxy forms as a smooth round shape, an elliptical.

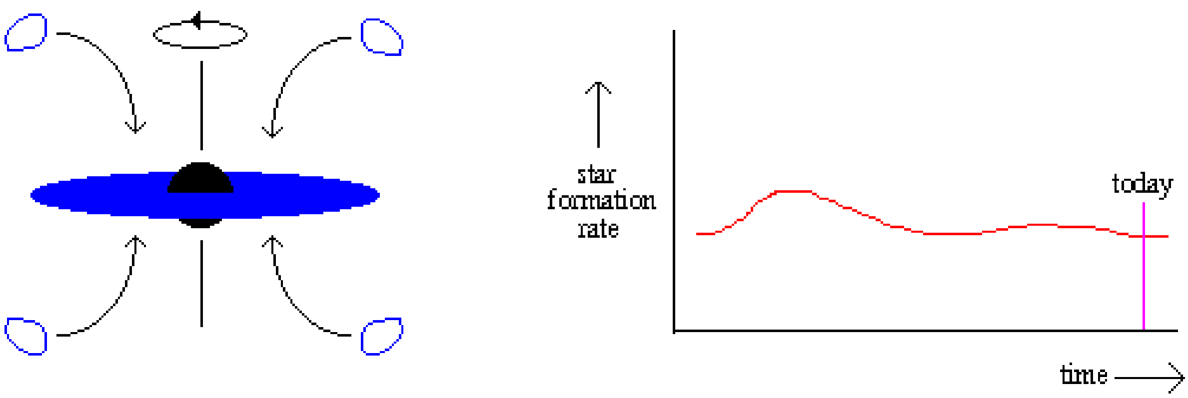
## Initial Star Formation Rates

the appearance of a galaxy is determined by its initial star formation rate, which determined if all its gas was used to make stars all in one burst, or slowly over billions of years

### Elliptical




### Spiral




Gas falling into a spiral disk is slowed by collisions and star formation continues till today. The spiral arms and patterns are due to ongoing star formation, whereas ellipticals used all their gas supplies in an initial burst 14 billion years ago and now have no ongoing star formation.

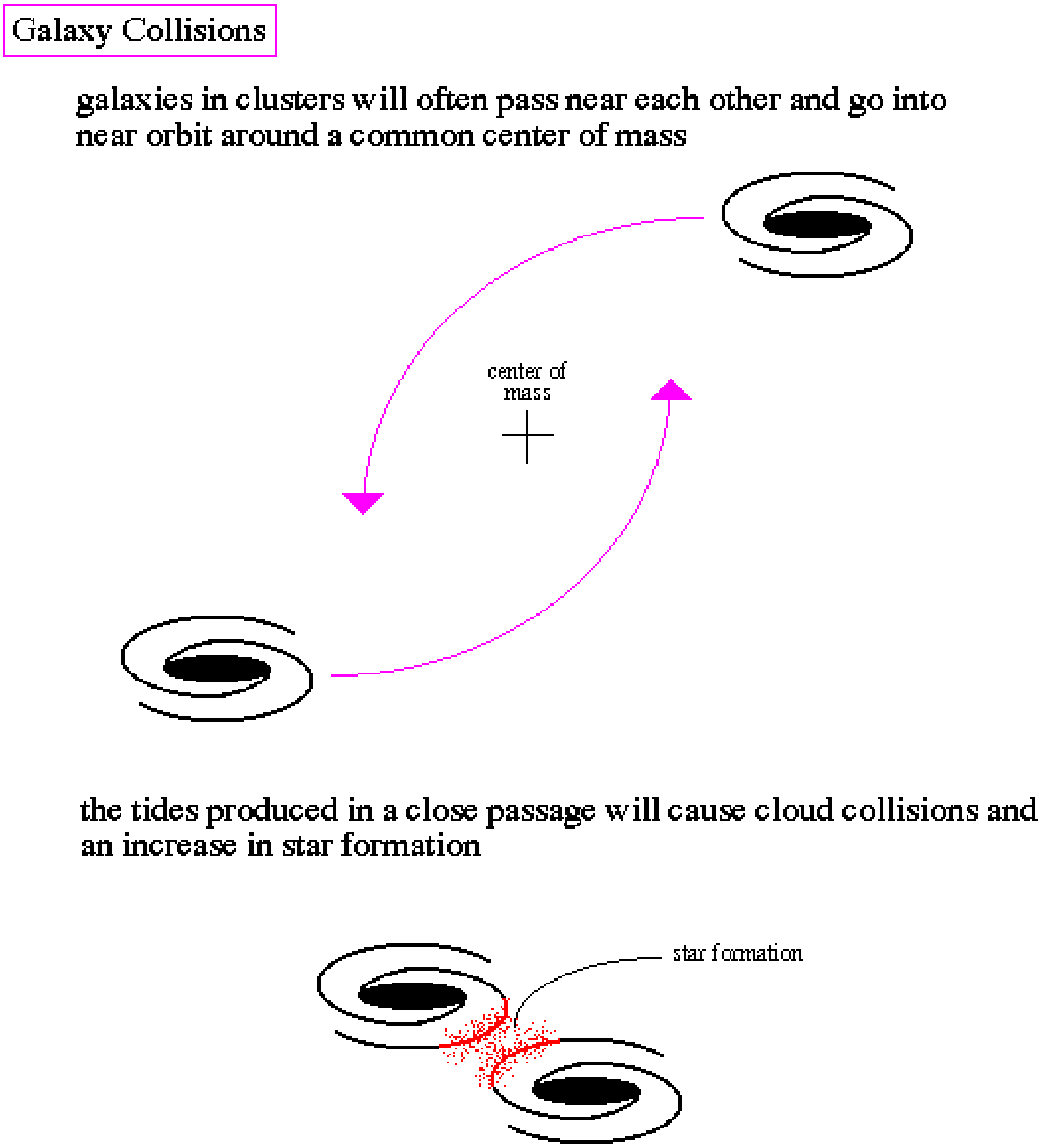
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Galaxy Mergers/Interactions :

After their formation, galaxies can still change their appearance and star formation rates by interactions with other galaxies. Galaxies orbit each on in

clusters. Those orbits can sometimes cause two galaxies to pass quite close to each other to produce interesting results.

Solid objects, like planets, can pass near each other with no visible effects. However, galaxies are not solid, and can undergo inelastic collisions, which means some of the energy of the collision is transfered internally to the stars and gas in each galaxy.

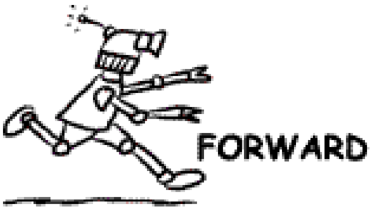


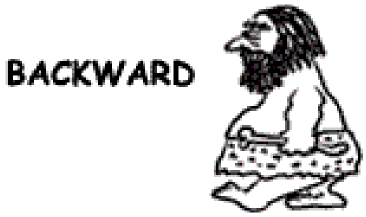

The tidal forces will often induce star formation and distort the spiral pattern in both galaxies.

If enough energy is transfered internally to the stars, then galaxies may merge.

Galaxy mergers are most frequent in dense environments, such as galaxy clusters.

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Universe Today :

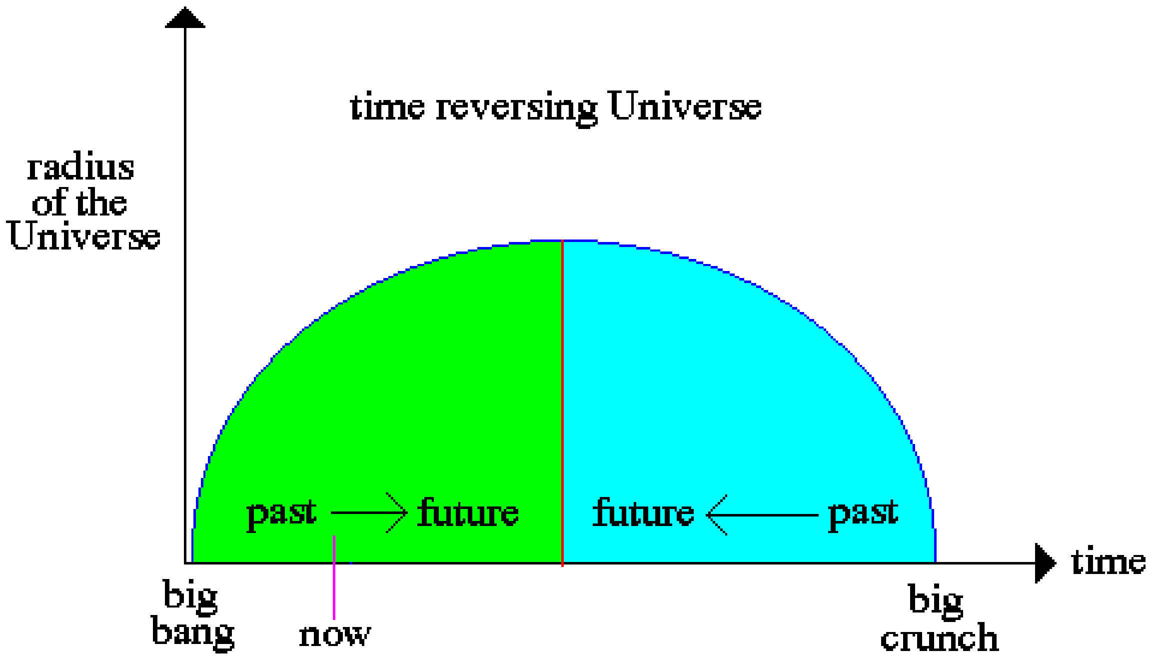
The present-day Universe is a rich collection of galaxies of many types, clusters of galaxies, large scale structure and exotic phenomenon (e.g. Galactic black holes). The galaxies themselves contain stars of all sizes, luminosities and colors, as well as regions of gas and dust where new stars form. We suspect that many stars have planets, solar systems in their own right, possible harbors of life.

So what's going to happening in the future??

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Time Reversal:

If the Universe is closed, then we might expect the arrow of time, as defined by entropy to reverse. There appears to be a natural connection between the expanding Universe and the fact that heat moves from hot areas (like stars) to cold areas (like outer space). So if the expansion of space were to reverse, then would entropy run the other way?




This kind of Universe has no real beginning or end, and is refered to as an oscillating Universe. Notice that it's impossible to determine which side you currently are on since time reverses and all appears normal to the observer.

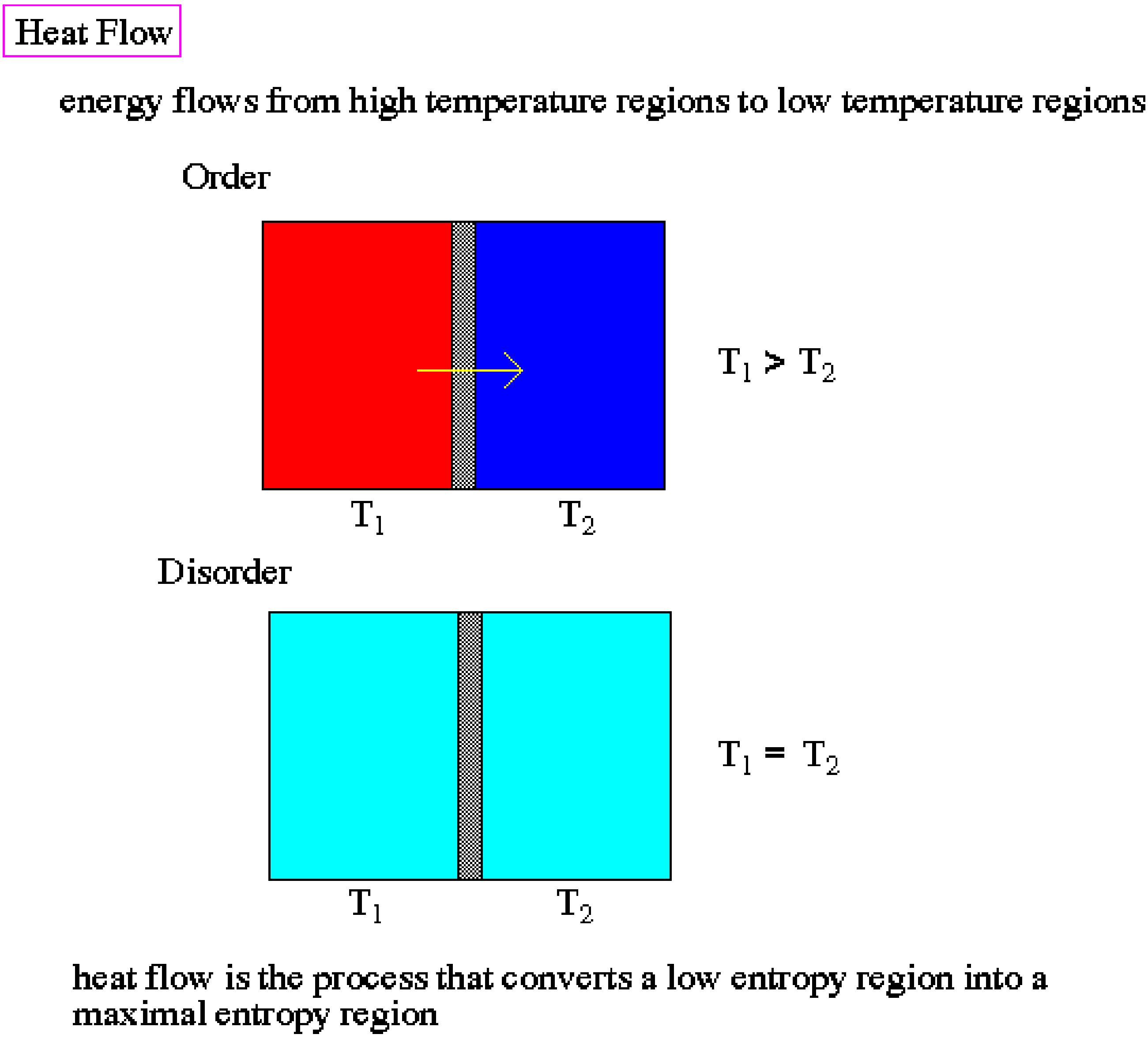
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The Fate of the Universe :

The past history of the Universe is one of an early, energetic time. As the Universe expanded and cooled, phenomenon became less violent and more stable.

This ruling law of Nature during the evolution of the Universe has been entropy, the fact that objects go from order to disorder. There are local regions of high order, such as our planet, but only at the cost of greater disorder somewhere nearby.

If the Universe is open or flat (as our current measurements and theories suggest) then the march of entropy will continue and the fate of our Universe is confined to the principle of heat death, the flow of energy from high regions to low regions.



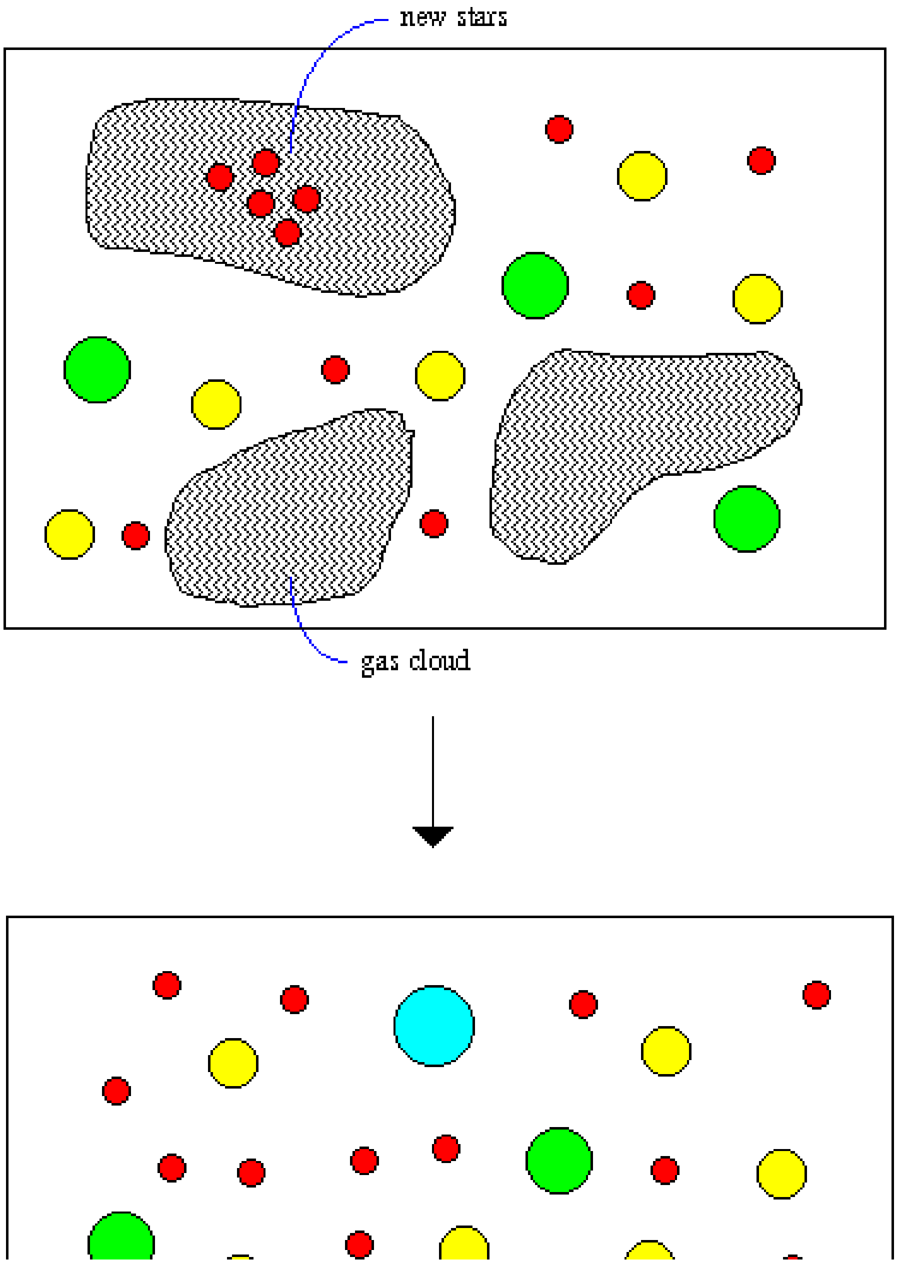
With this principle in mind, we predict the future of the Universe will pass through four stages as it continues to expand.

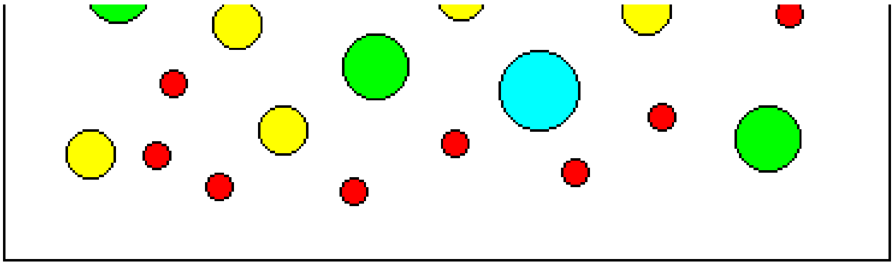
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Stellar Era :

The Stellar Era is the time we currently live in, where most of the energy of the Universe comes from thermonuclear fusion in the cores of stars. The lifetime of the era is set by the time it takes for the smallest, lowest mass stars to use up their hydrogen fuel.

The lower mass a star is, the cooler its core and the slower it burns its hydrogen fuel (also the dimmer the star is). The slower it burns its fuel, the longer it lives (where `live' is defined as still shining). The longest lifetime of stars less than 1/10 a solar mass (the mass of our Sun) is $10^{14}$ years.





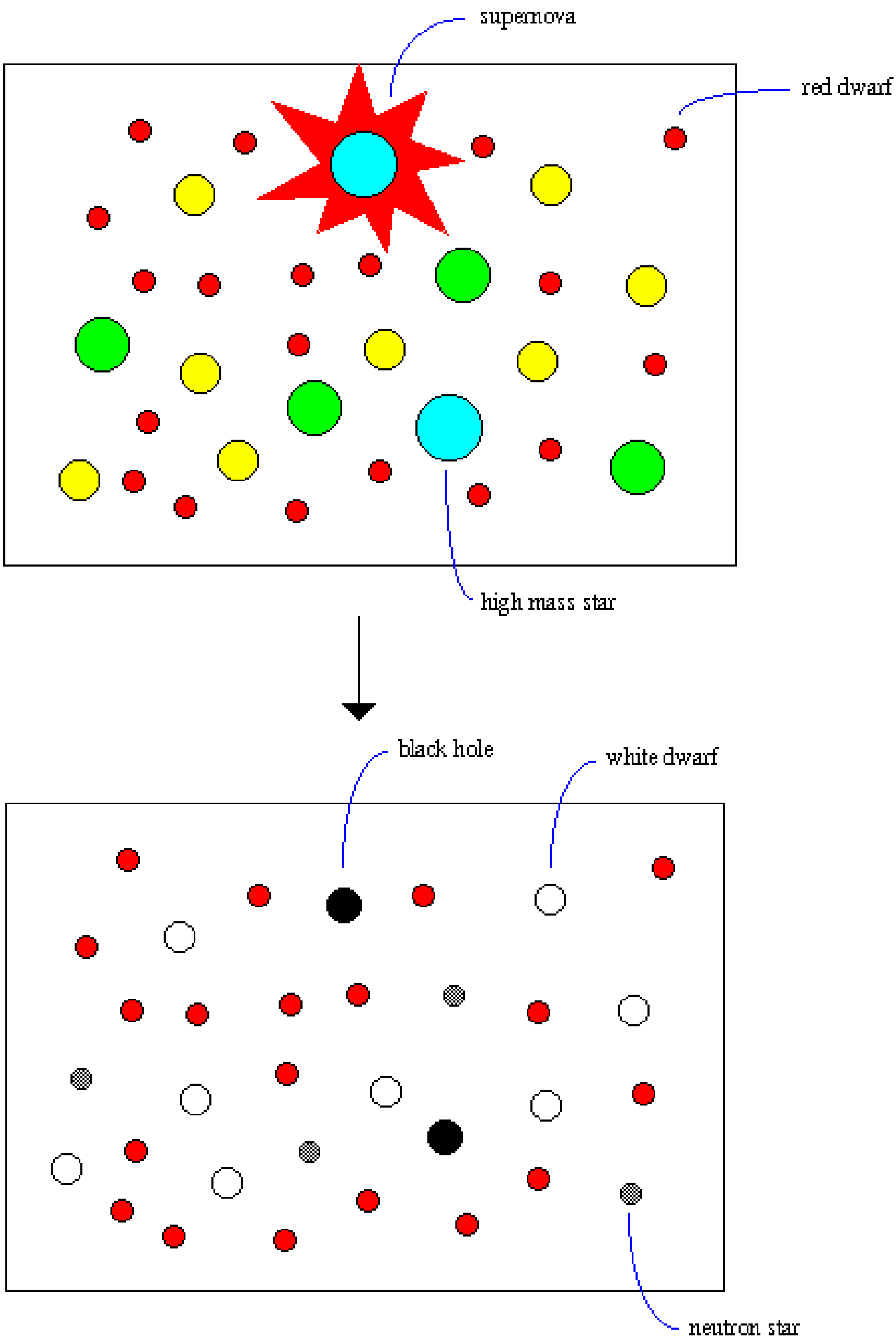
New stars are produced from gas clouds in galaxies. However, $10^{14}$ years is more than a sufficiently long enough time for all the gas to be used up in the Universe. Once the gas clouds are gone, all the matter in the Universe is within stars.

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Degenerate Era :

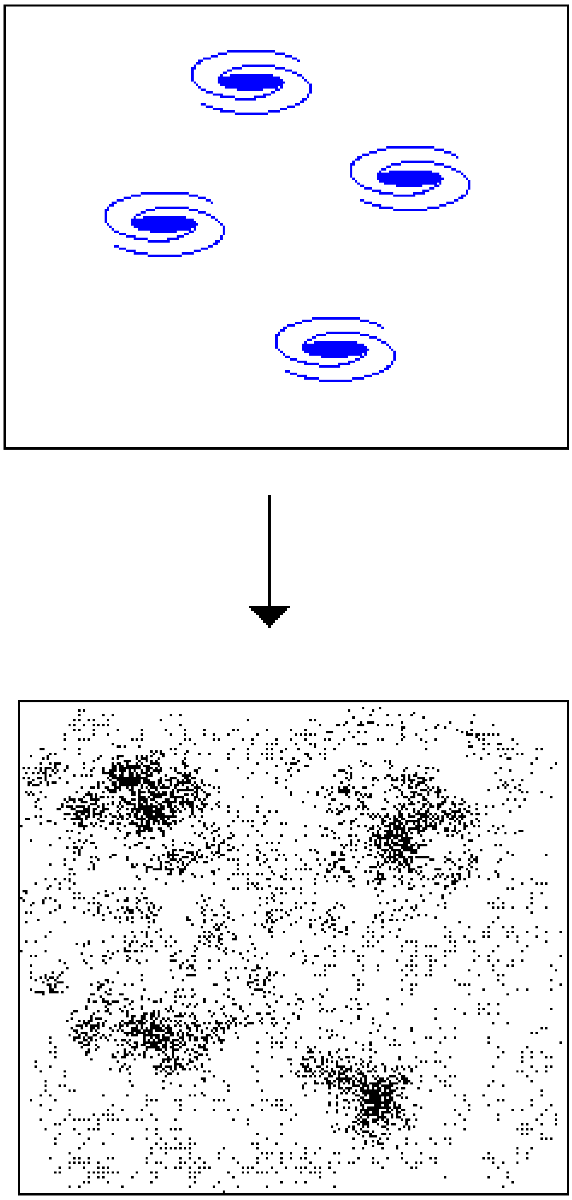
Once all the matter has been converted into stars, and the hydrogen fuel in the center of those stars has been exhausted, the Universe enters its second era, the Degenerate Era. The use of the word degenerate here is not a comment on the moral values of the Universe, rather degenerate is a physical word to describe the state of matter that has cooled to densities where all the electron shell orbits are filled and in their lowest states.

During this phase all stars are in the form of white or brown dwarfs, or neutron stars and black holes from previous explosions. White and brown dwarfs are degenerate in their matter, slowly cooling and turning into black dwarfs.




During this era, galaxies dissolve as stars go through two-body relaxation. Two-body relaxation is when two stars pass close to one another, one is kicked to high velocity and leaves the galaxy, the other is slowed down and mergers with the Galactic black hole in the center of the galaxy's core. In the end, the

Universe becomes filled with free stars and giant black holes, leftover from the galaxy cores.



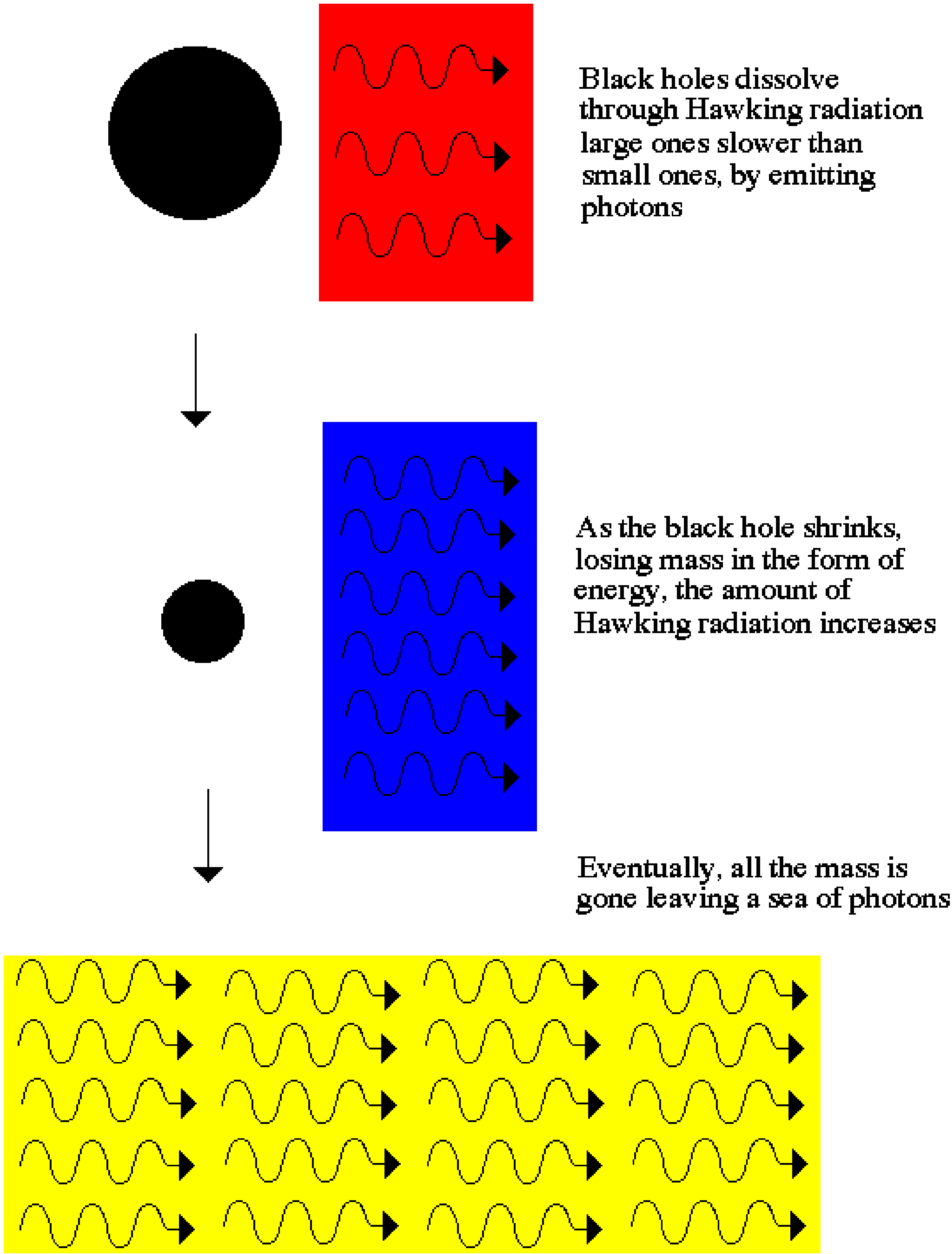
The Universe would evolve towards a vast soup of black dwarf stars except for process known as proton decay. The proton is one of the most stable elementary particles, yet even the proton decays into a positron and a meson on the order of once per $10^{32}$ years. Thus, the very protons that make up black dwarf stars and planets will decay and the stars and planets will dissolve into free leptons. This all takes about $10^{37}$ years.

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Black Hole Era :

Once all the protons in the Universe have decayed into leptons, the only

organized units are black holes. From Hawking radiation, we know that even black holes are unstable and evaporate into electrons and positrons.



This process is extremely slow, varying inversely as the mass of the black hole. For Galactic mass black holes the time to dissolve can last up to $10^{100}$ years. The result is a bunch of photons, slowly cooling in the expanding Universe.

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Dark Era :

After all the black holes have evaporated, the Universe consists of an expanding sea of very long wavelength photons and neutrinos. This is a system of maximum disorder, no coherent structures or objects. No sources of energy, and no sinks as well. The rest of time is simply a continual lower of energy until the state of quantum vacuum is reached.

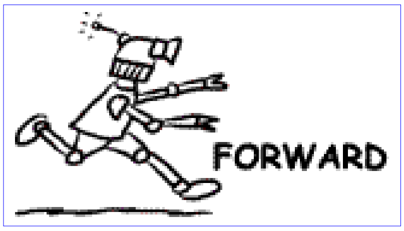
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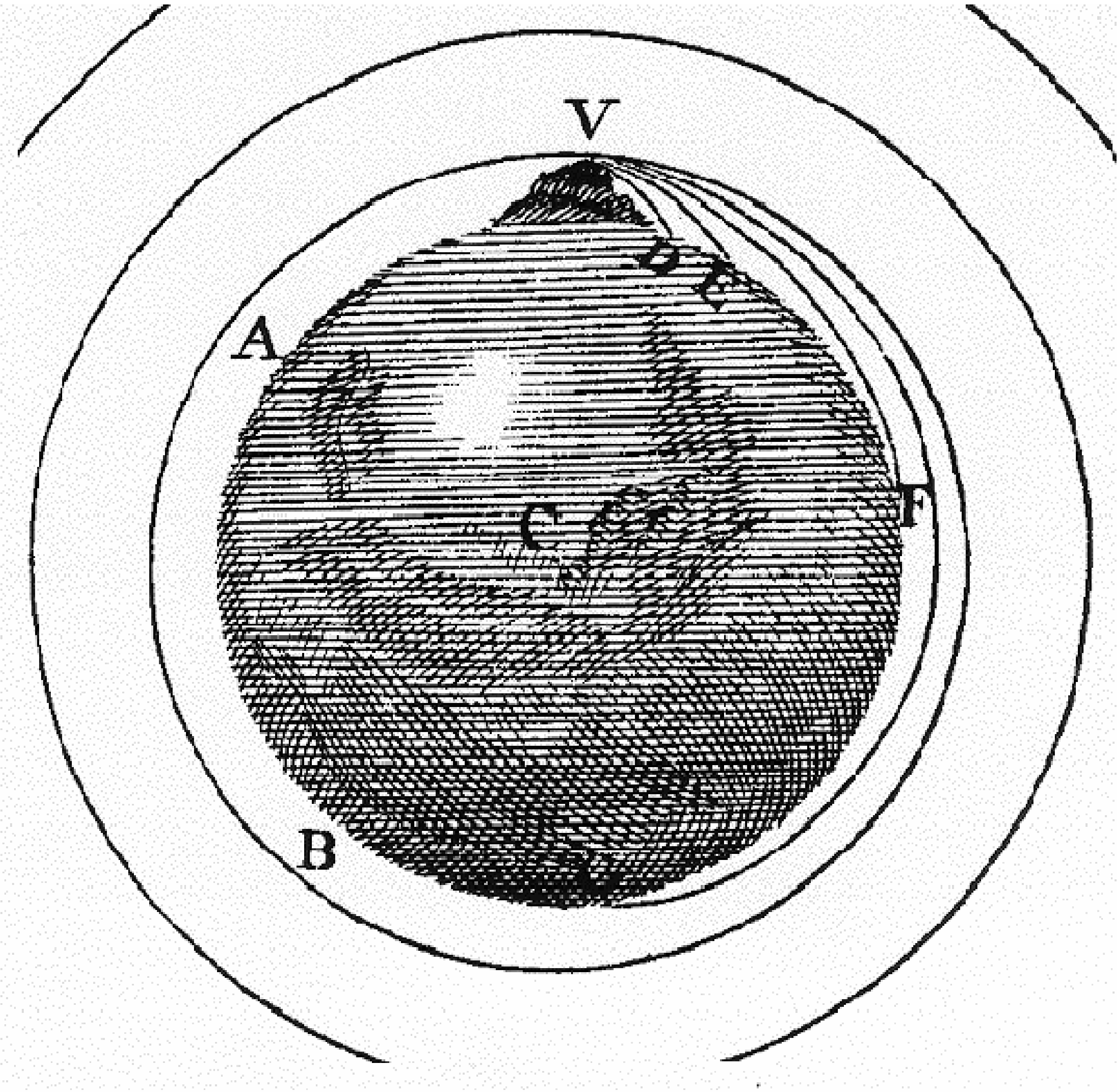
End of Time :

This course has been an exploration into modern cosmology and the search for the final laws of Nature (a theory of Everything) and the origin of Universe. Although there are many, many unsolved riddles to the Universe, the basic picture known as the Big Bang model is, at the very least, the foundation whose basic properties will always remain unchanged.

Although many of the concepts discussed in this course are strange, they are all based on rational scientific thought (the real world is stranger than anything you can imagine). A proper scientific model leaves less room for irrational beliefs. Understanding within the scientific method removes the blank areas on our maps, the place were we once drew monsters and golden cities. This knowledge dampens our fears like a candle in the dark.

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